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ASSESSMENT OF SYNTHETIC MEMBRANE SUCCESSES AND FAILURES AT WASTE STORAGE AND DISPOSAL SITES

by

Jeffrey M. Bass
Warren J. Lyman
Joseph P. Tratnyek

Arthur D. Little, Inc.
Cambridge, MA 02140

Contract No. 68-03-1771

Project Officer:
Mary Ann Curran
Land Pollution Control Division
Hazardous Waste Engineering Research Laboratory
Cincinnati, OH 45268

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

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16. ABSTRACT

Data from 27 lined facilities provided by five vendors was analyzed to determine the factors which contributed to success or failure of the liner at those facilities. The sites studied included a wide variety of wastes handled, liner types, geographic locations, facility ages, facility sizes, etc. Based on the definitions used in this study, the 27 facilities selected by the vendors had a total of 12 "failures" at 10 sites. At four or five of these sites groundwater contamination apparently resulted from the failures.

Two main elements of success at lined sites are considered to be: (1) a proper philosophical and conceptual approach; and (2) the extensive use of quality assurance programs in all facets and stages of a facility's operation. Other contributing factors include overdesign of system, presence of a knowledgeable customer, bidding to specifications, selection of qualified companies, cooperation amongst companies on liner job, conducting waste-liner compatibility tests, simplicity of design, and good weather.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandonded waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibily and economically.

This report describes factors which contributed to synthetic liner failure or success in lined storage and disposal facilities and will be useful to hazardous waste site designers, owners, operators and liner installers as well as regulatory agencies. For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

Data from 27 lined facilities provided by five vendors is analyzed to determine the factors which contributed to success or failure of the liner at those facilities. The sites studied included a wide variety of wastes handled, liner types, geographic locations, facility ages, facility sizes, etc. Based on the definitions used in this study, the 27 facilities selected by the vendors had a total of 12 "failures" at 10 sites. At four or five of these sites groundwater contamination apparently resulted from the failures. Some of the contributing factors, if not causes, for the failures noted include the following:

- Failure to control operations (at an operating site) so as to safeguard the liner;
- Poor (or inadequate) design work in general;
- Failure to use an independent, qualified design engineer;
- Poor (or inadequate) installation work in general;
- Poor or inadequate communication and cooperation between companies working on an installation job;
- The use of untrained and/or poorly supervised installers;
- Failure to conduct (or adequately conduct) waste-liner compatibility tests;
- Adverse weather conditions during installation;
- Use of old dump site, with contaminated soil, as site for lined facility;
- Selection of companies (for liner job) by processes that did not help ensure that good materials and workmanship would result;
- Selection of liner material by process not involving detailed bid specifications (prepared by design engineer, not liner manufacturer);
- Facility age (more failures were associated with the older sites).

Two main elements of success at lined sites are considered to be: (1) a proper philosophical and conceptual approach; and (2) the extensive use of quality assurance programs in all facets and stages of a facility's operation. Other factors noted as contributing to success included:

- Overdesign of system;
- Presence of a knowledgeable customer;
- Bidding to specifications;
- Selection of qualified companies;
- Cooperation amongst companies on liner job;
- Conducting waste-liner compatibility tests;
- Simplicity of design, and
- Good weather.

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ACKNOWLEDGEMENTS

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts, using data supplied by five subcontractors. These subcontractors are companies or individuals active in the liner technical community (e.g., as installers or fabricators). By mutual agreement the identities of these subcontractors are being kept confidential. We gratefully acknowledge the data and insight they provided to us for this program. We also acknowledge the guidance given by our Project Officer, Mary Ann Curran.

SECTION 1

INTRODUCTION

BACKGROUND

Under the Resource Conservation and Recovery Act (RCRA), the U.S. Environmental Protection Agency (EPA) has oversight responsibility for the land impoundment and disposal of hazardous wastes. A major objective of the EPA's regulations promulgated under the authority of RCRA is the protection of groundwater; more specifically, the prevention of groundwater contamination by liquid wastes or waste leachates which may enter the ground at hazardous waste treatment, storage or disposal facilities (TSDFs).

To this end, the EPA has promulgated regulations for the permitting of land impoundment and disposal facilities that place a heavy emphasis on the use of a liner system under the wastes[*]. A liner system is intended to act as a barrier to downward pollutant migration. The barrier may consist of a compacted layer of clay, a flexible membrane (plastic) liner (FML), asphalt, cement or suitable soil sealant. The EPA indirectly mandates the use of FMLs for landfill liners because they are the only materials perceived as being able to "... prevent wastes from passing into the liner during the active life of the facility" (U.S. EPA, 1982).

Other components of a liner system *may* include: a drain system above the primary barrier to collect leachate (mandatory for landfills); a second barrier layer with a leak detection system [drain] between it and the primary layer; a smooth, compacted subgrade with a gas vent layer; a soil or sand covering over the primary liner; and one or more geotextile fabrics to act as a separator between soil types or as a cushion to a FML.

The EPA has for some time understood the important role that such liner systems are required to play, and over the last ten years has carried out a number of research programs designed to improve the design of liner systems (with a special focus on waste-liner compatibility) and to evaluate the past performance of liner systems. Reports of particular interest in this regard include those by Matrecon, Inc. (1982), Haxo *et al*. (1982), Haxo *et al*. (1983), Lyman *et al*. (1983), RTI (1983), Schwope *et al*. (1983), and TRW (1983). Many issues related to liner design and use (as stipulated in the July 1982 regulations [US EPA, 1982]) were reviewed in a Regulatory Reform Analysis undertaken by the EPA in 1983; the findings of this study are summarized in a report by Earth Technology Corp. (1984).

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[*] These regulations were published in the *Federal Register* on July 26, 1982 and became effective on January 26, 1983 (U.S. EPA, 1982).

The evaluation of past performance of synthetic liners from actual site installations has been specifically covered in the reports by EMCON Associates (1983a, 1983b), and indirectly covered in the surveys reported by Lyman et al. (1983) and TRW (1983). The latter two studies, in particular, focused* on an analysis of actual or potential failure modes for synthetic liners. These failure modes might be associated, for example, with poor design, improper installation, or changing operations at the facility.

Also of interest is the report by Mitchell and Spanner (1984) for the U.S. Nuclear Regulatory Commission. While the report has some focus on the potential use of FMLs at uranium tailings ponds, it also contains: (a) a discussion of failure modes (based on case history studies); (b) liner compatibility data from tests using a simulated tailings environment; (c) an evaluation of seam inspection techniques; and (d) an evaluation of leak detection systems.

The four case studies of double-lined facilities reported by Montague (1981, 1982a, 1982b), while interesting, have been the subject of controversy. Data on volume flow rates and chemical composition of leak detection system fluids were used to conclude that the primary liner had failed in each case. In one instance, the site owner has claimed that the data only reflected the fact that rain had saturated the soil in the leak detection layer during the construction period before the primary liner had been put in place, and that the soil had suffered some cross contamination from a neighboring disposal site.

THE CURRENT STUDY

The current study was designed to supplement the existing information using a different approach that involved an in-depth evaluation of the factors leading to both "successes" and "failures" at a limited number of case study sites. A companion study, using the same general approach, was simultaneously carried out by Woodward-Clyde (1984).

A novel aspect of the approach used by Arthur D. Little, Inc., in its study was the use (under subcontract) of experts from companies (referred to as vendors) in the liner industry. Five such vendors agreed to provide information on lined facilities with which they had been associated. Each vendor was asked to select between 4 and 7 sites and to include both "successes" and "failures" within that group. Altogether, a total of 27 case histories were obtained; most of the sites selected by the vendors were waste impoundments of one kind or another, but not all would be considered hazardous waste sites.

In order to encourage maximum disclosure of information, especially where "failure" was involved, it was agreed that the identities of the vendors and the individual sites described would be held confidential by Arthur D. Little, Inc. Essentially all of the information provided to Arthur D. Little, Inc. by these vendors was in the form of a questionnaire response for each site (along with supporting drawings, design specifications, etc.) and a summary report. Vendors were asked to supply as much detail as possible, but were told that they were under no obligation to supply information that was not in their files or was not easily ascertainable. Data and summary reports on the 27 facilities supplied by the five vendors are analyzed in this report.

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* The TRW study addresses installation practices for both clay and synthetic liners.

REPORT OVERVIEW

Section 2 and Section 3 provide summary conclusions and recommendations, respectively. Additional details on recommendations for future research are given in Section 7.

Section 4 provides a brief discussion of the approach used in this study, outlines the important subject areas covered by the questionnaire, and describes the nature of the responses received.

Section 5 provides a number of summary tables allowing a rapid comparison of the 27 sites covered in this report.

Section 6 includes analyses of the data submitted to Arthur D. Little, Inc. and a discussion of the factors that may have contributed to the "successes" and "failures".

Section 7 gives a detailed discussion of recommendations for future research or action.

Appendix A provides a copy of the questionnaire that formed the basis for each vendor's submission of data for each site.

Appendix B gives the summary, letter-style report requested from each of the five vendors. These reports contain their own conclusions and recommendations based upon the totality of the vendor's experience, not just the few selected case studies described in this report.

Appendix C provides a summary description of each of the 27 sites.

VENDOR AND SITE CODING

As noted above, the names of all vendors and sites are being held confidential by mutual consent of Arthur D. Little, Inc. and the vendors. The reader will thus find all such names and sites have been coded in this report and in the appended vendor reports. The five vendors are referred to as V1, V2, V3, V4 and V5. The sites described by a particular vendor are designated by numbers following the vendor code, e.g. site V2-3 is the third site described by vendor V2. In addition, the names of any other companies involved with a site (e.g., as general contractor, design engineer, resin manufacturer) are being held confidential.

CAVEATS

The reader should be aware of several weaknesses in the data base used for this report which may limit the extraction of statistically valid summaries, or of generalities which can be applied to the liner systems currently being installed at hazardous waste sites.

- Data were collected for 27 sites selected by the vendors to reflect factors which contribute to failure or success of liner systems. The sites therefore cannot be considered a statistically valid sample of all in-place liner systems, and there is likely to be some disproportionate representation of key variables (e.g., location, age, liner material type versus failure).

- Several of the sites cannot be considered as hazardous waste treatment, storage or disposal sites. The types of liquids or wastes contained include, for example, municipal and industrial waste water, oil field brines, municipal solid waste, power plant ash, in addition to hazardous chemical wastes.

- The amount of information provided by the vendors for each site was highly variable. Since the vendors could only be asked to provide information from their own files, many questions went unanswered if the data were unavailable.

- There was also some variability in the quality of the data provided. Some responses came complete with numerous detailed blueprints; others had hand drawn sketches or no diagrams at all. There were some minor inconsistencies in the data, and a few instances when vendor pride in their product or service may have resulted in some loss of objectivity in the assessments reported on the questionnaires.

The caveats listed above are not considered to detract in a major way from the value of the information collected and reported herein. On the contrary, this study has proved to be a valuable learning exercise and should be followed by similar studies in the future. However, use of information from this report should be consistent with the limitations of the data base as described above.

SECTION 2

CONCLUSIONS SUMMARY

This study included an evaluation of data from 27 lined waste impoundments constructed between 1971 and 1983. All data used in the study were provided by five subcontractors (referred to as vendors) and were supplied in the form of questionnaire responses with supporting documents and letter-style reports. The purpose of the analyses carried out by Arthur D. Little, Inc. was to evaluate the apparent reasons for successes and failures in the liners at these sites. Because the study was based on a limited number of sites, and because the vendor-supplied data were at times incomplete, some care must be used in drawing overly broad conclusions. (See Section 1 for more discussion of such limitations.)

FACTORS CONTRIBUTING TO FAILURE

The vendors had been requested to supply data on a variety of sites including some that had had problems and others that were clearly successes. In our analysis, we defined a "failure" in the pre-operational period as any condition of the liner which required non-routine corrective measures to make the liner suitable for planned operations. A failure during operations was defined as any condition of the liner which caused (or threatened to cause) groundwater contamination, or otherwise caused operations to cease because of observed abnormalities.

Based on the above definitions, the 27 facilities selected by the vendors had a total of 12 "failures" at 10 sites. At four or five of these sites groundwater contamination apparently resulted from the failures. While corrective actions were taken at all sites, one was unable to be repaired sufficiently for operations to continue. At 4 of the 10 sites with failures, the failure was of such a relatively minor nature (and without release of pollutants to the environment) that, after liner repair, they could be considered qualified successes. Thus, 21 of the 27 sites analyzed could be considered complete or qualified successes, based on available data.

The nature of the "failures" noted included chemical attack of the liner (1 or 2 sites), physical tears or punctures (5 sites), problems with field seaming or other liner installation activities (1 to 3 sites), and large gas bubbles, called "whale-backs", under the liner (1 site).

In our analysis to identify the causes of these failures we recognized not only the immediately-preceding action (e.g., subsoil gas generation in high water table area leading to "whale-backs"), but prior categorical or process failures that might be associated, for example, with poor design, lack of quality control, or communications failures between companies. We also recognized that even these categorical failures may be preceded by philosophical or conceptual failures wherein misconceptions or lack of concern about liner systems are a root cause of some subsequent failure. This type of analysis thus recognizes a hierarchy of failure modes with one type of failure potentially leading to another (i.e., a propagation of errors) until some ultimate failure (e.g., a rip in the liner) occurs. (Section 6 provides further discussion of this failure mode analysis.)

Some of the contributing factors, if not causes, for the failures noted in our case studies include the following:

- Failure to control operations (at an operating site) so as to safeguard the liner;
- Poor (or inadequate) design work in general;
- Failure to use an independent, qualified design engineer;
- Poor (or inadequate) installation work in general;
- Poor or inadequate communication and cooperation between companies working on an installation job;
- The use of untrained and/or poorly supervised installers;
- Failure to conduct (or adequately conduct) waste-liner compatibility tests;
- Adverse weather conditions during installation;
- Use of old dump site, with contaminated soil, as site for lined facility;
- Selection of companies (for liner job) by processes that did not help ensure that good materials and workmanship would result;
- Selection of liner material by process not involving detailed bid specifications (prepared by design engineer, not liner manufacturer);
- Facility age (more failures were associated with the older sites).

FACTORS CONTRIBUTING TO SUCCESS

Success was defined in this study as the converse of failure, i.e., non-routine corrective measures were not required, the liner did not leak, and operations were not shut down. Finding the reasons for success is more difficult than for failure; it is essentially asking why everything went right. Clearly, no one action can be credited with a resulting success as, by contrast, it could for a failure. Thus, in providing a synthesis and independent evaluation of the apparent reasons for success at the study sites it is necessary to hypothesize to some extent.

Two main elements of success at lined sites are considered to be: (1) a proper philosophical and conceptual approach; and (2) the extensive use of quality assurance programs in all facets and stages of a facility's construction and operation. The desired philosophical approach requires that the responsible individuals (owner, designer, general contractor, installer, etc.) understand the importance of what they are doing and appreciate the complexities (and associated technical problems) that will be attendant. A key element of this approach is: (1) to assume that there will be problems; (2) to examine the possible consequences of those problems; and then (3) to take the appropriate steps (e.g., design changes, quality control plans) to avoid or minimize the problems.

Success is also more likely to result if the general approach described above is applied to all stages or facets of a liner system including design, material and contractor selection, site preparation, liner installation, facility operation, and closure. Within each of these areas, the generalized approach should be applied within the framework of a formal quality assurance program. It is worth noting that at least 23 of the 27 sites in this study had some form of a quality assurance program for one or more critical operations (primarily liner manufacture, fabrication and installation), although the quality of these programs could not be assessed from the data submitted by the vendors.

Other factors noted as contributing to success included:

- Overdesign of system;
- Presence of a knowledgeable customer;
- Bidding to specifications;
- Selection of qualified companies;
- Cooperation amongst companies on liner job;
- Conducting waste-liner compatibility tests;
- Simplicity of design, and
- Good weather.

SECTION 3

RECOMMENDATIONS SUMMARY

The purpose of this section is to provide a brief summary of what appear to be the most important areas for future work that will help ensure safe and reliable operations at lined RCRA facilities. Recommendations of four different types are included:

- Research projects
- Education
- Quality assurance: planning and implementation
- Preparation of guidance documents

RESEARCH PROJECTS

This study analyzes the factors which contribute to success and failure at lined facilities, but does not provide a statistical basis for determining the actual significance of these factors. A statistically valid study could be conducted using the experience gained in conducting the present study to verify the conclusions of the present study and quantify the significance of failure and success factors at liner sites. The study could address the following questions, among others:

- Are older facilities more likely to experience failure? By what mechanisms?
- Are larger facilities more likely to experience failure? By what mechanisms?
- How do QA/QC programs at various levels contribute to success?
- How are the various success and failure factors evident at sites which have experienced problems? At sites which have not experienced problems?
- What is the apparent "success" rate for FML installations of various types?
- How well do RCRA-designed sites perform in comparison with non- or pre-RCRA sites?

Only two sites in this study did not use a flexible membrane liner (FML) as the primary liner. Consequently, little was learned in general about the reasons for success and failure for other types of liners such as soil cement, asphalt, and spray-on. Additional research, including more case studies focusing on facilities with such liners, would be desirable.

Vendor V3 provided a number of more specific research recommendations (listed in Section 7 and Appendix B) covering such areas as seaming technology, leachate hydraulics, FML durability under hydraulic stress, long-term waste-liner compatibility tests and an evaluation of accelerated leachate-liner compatibility tests. Vendor V1 suggested that development of a set of consistent quality standards for FMLs, and the development of test protocols by which related FML properties would be measured.

EDUCATION

Section 6 of this report describes how important the proper philosophical and conceptual approach is to "success" for a lined site. Key elements of this approach are: (1) to assume that there will be problems; (2) to examine the consequences of those problems and/or "failures"; and then (3) to take the appropriate steps to avoid or minimize the problems. To help foster the desired approach, a conscious effort should be made to continue educating concerned parties (industry, design engineers, installers, etc.) about the issues, problems, and solutions relating to the installation and use of lined facilities. This can be done by a variety of means including regional workshops, conferences where technical papers can be presented, and reports publication. All of these are currently being done to some extent, and it is strongly recommended that education continue to be emphasized.

In addition to the above, it is recommended that the EPA prepare a special annotated bibliography of important reports and publications covering liners. A significant amount of information is available, but few people are generally aware of it. Newsletters (which could be distributed free or as part of recently-initiated trade journals on geomembranes) that covered EPA activities related to liners would also be welcome.

QUALITY ASSURANCE: PLANNING AND IMPLEMENTATION

Much higher assurance of success will be associated with facilities built and operated within the framework of one or more quality control or quality assurance (QA) programs. These programs should cover all stages of a facility's life: design, material selection, site preparation, liner installation (including thorough seam integrity inspection), facility operation and closure.

It is recommended that guidance in the preparation and implementation of quality assurance programs be prepared. This guidance should be as detailed as possible, and backed up by examples and the availability of technical consulting from the EPA or its contractors.

Preparation and use of QA plans should also be considered as a regulatory requirement for a RCRA permit.

PREPARATION OF GUIDANCE DOCUMENTS

The EPA has prepared over a dozen Technical Resource Documents (TRDs) as well as other reports providing guidance on many aspects of hazardous waste treatment, storage and disposal. This study showed that such documents are very important for lined installations, and that guidance documents should be prepared or updated to cover (or expand their coverage on) subjects such as the following:

- Operating procedures that safeguard the liner system;
- Writing bid specifications for liner materials or installations;
- Best use of geotextiles in liner systems;
- Methods to evaluate potential for gas generation in subsoils;
- Acceptability of using old disposal areas for new RCRA sites;
- Obtaining coordination and cooperation from the several companies involved in a liner job;
- Sealing FMLs around appurtenances;
- Specifications for selection and preparation of subgrade materials to be used under FMLs; also need to describe methods to test this subgrade (after placement) for proper density and moisture content.
- Methods to test the completeness of seam closures in a liner installation.

SECTION 4

APPROACH

The data on lined disposal sites and liner systems described in this report were obtained from five subcontractors (referred to herein as 'vendors'). The general approach that was used to obtain and analyze these data involved five steps:

Step 1 - Identification of, and preliminary negotiation with, prospective vendors;

Step 2 - Design of questionnaire to be used (by vendors) for each site chosen;

Step 3 - Issuance of subcontracts and instructions to vendors;

Step 4 - Receipt of vendor reports and preparation (by Arthur D. Little, Inc.) of summary reports on each site, including computer encoding of textual answers to each question;

Step 5 - Review of all data and vendor reports (by several Arthur D. Little, Inc. technical specialists) to identify factors contributing to successes and failures.

It was agreed from the beginning that the identities of all vendors, as well as the identities of all site owners and other companies involved in work at the site, would be held confidential. This rule, and the use of Arthur D. Little, Inc. as an intermediary between the EPA and the vendors, made it possible for the EPA to benefit from the experience of the vendors without gaining access to proprietary (uncoded) information. The process also encouraged the vendors to provide detailed and honest assessments for their selected sites, especially if there had been problems.

The first step in our approach was not without problems. At one point we were negotiating with seven vendors, each of whom had a variety of sites to offer and special concerns that had to be dealt with. New potential vendors were added as some from the initial list dropped out. In final negotiations, the number of sites to be covered by each vendor was adjusted to be consistent with the total budget available for subcontractor work.

The questionnaire that was designed for use in this program is shown in Appendix A.

In the issuance of instructions to the selected vendors (Step 3 in the list above), they were told that the sites studied were to be selected according to the following criteria:

1) The site had a liner which failed, or encountered difficulties that were corrected, or was considered a notable success;
2) Good information on the site was available to complete the questionnaire;
3) The site was used to dispose of or store hazardous materials; and
4). The sites together represented a variety of liner types, materials contained, and/or facility sizes.

In responding to the questionnaires for each site, the vendors were instructed to answer as many questions as possible based on information which was on file or readily obtainable. In addition to completed questionnaires for each site, the vendors were requested to supply supplementary information (e.g., reports, site location drawings, blueprints, specification sheets) whenever possible. The vendors were also asked to prepare a short summary report containing conclusions (regarding factors relating to successes and failures) and recommendations. The vendors' summary reports are reproduced (in coded form) in Appendix B of this report.

The fourth step in our approach involved a preliminary review of the data submitted by the vendors and the preparation of summary reports (for each site) for subsequent review by in-house technical specialists. In the subsequent review process (Step 5), each technical specialist was asked to focus on one or more specific areas related to their expertise (e.g., liner selection process; site design and location; liner installation; waste-liner compatibility testing). The principal findings of these technical specialists are given in Section 6 of this report.

SECTION 5

OVERVIEW OF SITES IN SURVEY

LINER SITES

Table 1 provides summary information on the 27 liner sites for which data were collected. A brief discussion is provided below.

Geographic Location

All sites are in the United State except for one in Canada. The number of sites in generalized locations in the United States is as follows:

North: 5
South: 5
Southwest: 2
Southeast: 1
East 4
East central: 1
West: 6
Midwest: 2

Principal Activity at Site

A range of activities is evident from the list in Table 1. The number in generalized categories are:

Waste treatment/disposal site: 8
Chemical plant: 6
Petroleum refinery: 3
Paper mill: 3
Petroleum Storage: 2
Electric power plant: 2
Uranium mill or mine: 2
Gas compressor station: 1

Type of Lined Facility

Seven (7) of the lined sites were landfills for solid wastes or drummed wastes. The remaining twenty (20) sites were surface impoundments classified by the vendors as follows:

Classification	No.
Surface impoundment	10
Reservoir (wastewater)	4
Lagoon	3
Aeration basin	2
Evaporation pond	1

TABLE 1. SUMMARY INFORMATION ON LINER SITES

Site ID	Site Location	Principal Activity at Site	Type of Lined Facility	Material Contained	Date Installed	Status (12/83)	Problems with Liner
V1-1	South	Petroleum product storage	Reservoir	Oil field brine	3/81	Open	--
V1-2	South	Petrochemical storage	Reservoir	Oil field brine	10/82	Open	Yes
V1-3	Southeast	Waste management	Landfill	Incinerator wastes	11/80	Open	--
V1-4	East	Waste management/landfill	Landfill	Solid wastes	9/80	Open	--
V1-5	South	Chemical plant	Surf. Impd.	Liquid chemical wastes	7/80	Open	--
V1-6	East central	Chemical plant	Landfill	Solid wastes, chemicals	6/81	Closed	--
V2-1	South	Paper mill	Aeration basin	Wastewater	-/73	Open	Yes
V2-2	Midwest	Paper mill	Aeration basin	Wastewater, pulp liquor	5/72	Closed	Yes
V2-3	West	Chemical plant	Surf. Impd.	Liquid, with salts	3/71	Open	Yes
V2-4	East	Chemical plant	Landfill	Chemical process sludge	8/74	Open	--
V3-1	North	Dredge spoil disposal	Surf. Impd.	Dredge spoil	4/83	Open	Yes
V3-2	North	Sanitary Landfill (type II)	Landfill	Solid Waste (some chem.)	7/77	Open	Yes
V3-3	Midwest	Wastewater treatment	Lagoon	Domestic sewage	9/82	Open	--
V3-4	North	Landfill	Landfill	Solid waste (munic. and ind.)	-/75	Open	Yes
V3-5	North	Paper mill	Surf. Impd.	Waste sludge and liquids	9/82	Open	--
V4-1	Canada	Uranium mining	Reservoir	Water, with metals, organics	9/83	Open	--
V4-2	South	Petroleum refinery	Reservoir	Oil field brine	11/83	Open	--
V4-3	Southwest	Electric power plant (coal)	Evap. pond	Wastewater	8/83	Open	--
V4-4	North	Waste management/landfill	Landfill	Drummed chemical wastes	7/82	Open	--
V4-5	East	Waste managmeent/disposal	Lagoons	Landfill leachate	12/80	Open	--
V4-6	East	Chemical plant	Lagoons	Liquid chemical wastes	6/80	Open	--
V4-7	West	Electric power plant	Surf. Impd. (8)	Water; wastewater; flyash	9/81	Open	--
V5-1	West	Petroleum refinery	Surf. Impd. (4)	Process Liquids	10/80	Open	Yes
V5-2	Southwest	Uranium mill	Surf. Impd.	Wastewater	6/79	Open	Yes
V5-3	West	Petroleum refinery	Surf. Impd.	Liquids	8/78	Closed	--
V5-4	West	Nat. gas compressor station	Surf. Impd.	Cooling tower blow down	-/74	Open	Yes
V5-5	West	Chemical plant	Surf. Impd.	Process water (with organics)	-/74	Open	--

The ten (10) surface impoundments that were not more specifically categorized served as temporary storage sites for liquid wastes.

Contained Materials

All of the materials which were to be contained within the lined sites were waste liquids, sludges, and/or solids. (Only one of the eight lagoons at site V4-7 was for fresh water.) In most cases the vendors were unable to supply detailed informaton on the composition of these wastes. It is clear that a variety of inorganic and organic chemicals were present in these wastes. However, it is not clear which wastes would be considered hazardous under the current RCRA regulations.

Date Installed

The dates (month/year) shown in Table 1 generally reflect the time when the site work and installation were completed. In many cases initial steps in the site work were completed several months (years in a few cases) prior to the dates shown. The number installed in each year are as follows:

Year	No.	Year	No.	Year	No.
'71	1	'76	0	'80	6
'72	1	'77	1	'81	3
'73	1	'78	1	'82	4
'74	3	'79	1	'83	4
'75	1				

Thus, nearly two-thirds of the selected sites were completed in the '80s, and have been in operation for three years or less.

Status

Of the 27 sites, three are currently closed (V1-6, V2-2 and V5-3).

Problems With Liner

The last column in Table 1 has a "yes" if the vendor described one or more problems that could be considered a liner "failure", even if the problem was subsequently repaired. The nature and cause of these failures are discussed in Section 6.

According to this summary, there were ten (10) sites that experienced failures and seventeen (17) that did not. Note that this success/failure ratio should be considered more a reflection of the vendors efforts to provide data on a variety of types of sites (including some that were successes and failures) than a reflection of all sites currently existing in the US. It is also possible that some of those for which no problems were reported could have current (unknown) or future problems. However, it is the experience of many people that, if problems are going to show up, they will do so within one to two years after installation. This clearly does not hold for such failures as hidden liner leaks under a landfill (which might take many years to detect), but probably is valid for many of the common "failures" associated with liner installation and exposed liners.

LINER SYSTEMS

Table 2 provides summary information on the liner systems used at each site. A brief discussion is given below.

Single vs Double Liner

Most of the sites (approx. 20) had only a single impermeable layer in the liner system. Some of the sites had both a flexible membrane liner (FML) and a layer of compacted clay, with or without a drain layer (leak detection system) in between. Such systems, along with others that had two FMLs, are listed in Table 1 as having a double liner. One site had a triple FML system.

Primary Liner Material

Flexible membrane liners (FMLs) were used at 25 of the 27 sites. Site V3-4 used a soil sealant applied at a rate of 25 tons per acre and mixed to a depth of 4 inches. Site V3-5 used 5 inches of asphalt cement. Top layers of soil cement were used at two sites (V1-1 and V5-3). A spray-on liner (called Chevron Industrial Membrane [CIM]) was used at site V5-1.

The abbreviations used for the flexible membrane liners are as follows:

Abbr.	Polymer Type	No. of Sites
CIM	Chevron Industrial Membrane (not a FML) (composition unknown)	1
CPE	Chlorinated polyethylene (OR = oil resistant)	5
HDPE	High density polyethylene	7
CSPE	Chlorosulfonated polyethylene	6
PO	Polyolefin	1
PVC	Polyvinyl chloride	9

The suffixes (R) and (U) placed after the FML abbreviations in Table 2 stand for 'reinforced', and 'unreinforced', respectively. A reinforced FML is one that incorporates (usually bonded between two polymer sheets) an open fabric or scrim, typically made of polyester or nylon. HDPE and PVC liners are usually not reinforced, while CSPE and, to a lesser extent, CPE are usually reinforced.

All of the FMLs commonly used today to line waste treatment or disposal sites are well represented by the sites selected for this study.

Primary Liner Thickness

Amongst FML liners, those made of HDPE are usually the thickest. This extra thickness is required, in part, to prevent problems during field seaming

TABLE 2. SUMMARY INFORMATION ON LINER SYSTEMS

Site ID	Single (S) or Double (D) Liner	Primary Liner Material*	Primary Liner (mil)	Total Surface Area (ac)	Exposed (E) or Buried (B)	Monitoring System	Layers in Liner System** (Bottom to top)	Air Vents	Problems with Liner
V1-1	S	OR-CPE(R)	36	10	B	No	Gr/GeoTex/S&G/GeoTex/FML/Soil cement	Yes	--
V1-2	S	CSPE (R)	36	22	E	Yes	Comp Clay/S/FML	Yes	Yes
V1-3	S	PVC (U)	30	2	B	No	Lime Rk/S/FML/S/Lime Rk	No	--
V1-4	S	PVC (U)	30	10	B	No	Comp Soil/FML/Soil	No	--
V1-5	D	PVC (U), CSPE (?)	20,36	1	E	Yes	Comp clay/S/FML/S/FML	Yes	--
V1-6	S	PVC (U)	30	2	B	No	Old Fill/Clean fill/FML/clay	Yes	--
V2-1	S	CSPE (R)	30	120	E	No	Comp clay and limestone/FML	Yes	Yes
V2-2	S	CSPE (R)	30	8	E	No	Comp soil/S&G/FML	No	Yes
V2-3	S	CSPE (U)	30	2.3	E	No	Comp Sub-base/FML	No	Yes
V2-4	S	CSPE (R)	30	4.3	B	Yes	Comp Fill/FML/S/G	No	--
V3-1	S	PO (R)	30	42	B	Yes	Prepared limestone/FML/Stone	No	Yes
V3-2	S	PVC (U)	20	75	B	Yes	Comp Clay/FML/S	No	Yes
V3-3	S	PVC (U)	20	8	B	No	Comp Soil/FML/S	No	--
V3-4	S	Soil Sealant	4 in.	25	B	Yes	Comp Sand/Liner/S	No	Yes
V3-5	S	Asphalt-concrete	5 in.	2	E	Yes	Comp. Soil/Ashpalt (2 lifts)	No	--
V4-1	S	HDPE (U)	100	18	E	Yes	Comp Sand/FML	No	--
V4-2	D	HDPE (U)	100	18.5	E	Yes	Comp Clay/S/FML	Yes	--
V4-3	S	HDPE (U)	80	88	E	No	Comp Subgrade/FML	Yes	--
V4-4	D	HDPE (U)	80	6	E (sides)	Yes	Clay/S/Comp Soil/FML/Comp Soil	Yes	--
V4-5	D	HDPE (U)	80	3.2	B	Yes	Comp clay/FML/Comp clay	No	--
V4-6	S	HDPE (U)	100	0.3	E	Yes	Comp Soil/FML	No	--
V4-7	S	HDPE (U)	80	66	E (sides)	No	Subgrade/FML/S (bottom only)	No	--
V5-1	3D,1S	CPE (U), CPE (U)	20, 30	1,5	E (CIM only)	Yes	Subgrade/CPE/Soil/Concrete/CIM	No (?)	Yes
V5-2	S	CPE (U)/PVC (U)	20/10	13	B	Yes	Nat. Soil/FML/Nat. Soil	No	Yes
V5-3	S	CPE (U)	30	0.7	B	Yes	Nat. Soil/FML/Nat. soil/soil cement	No	--
V5-4	D	PVC (U)	20	1.4	B	Yes	Comp Soil/Clay/S/FML/Nat. Soil	No (?)	Yes
V5-5	Triple	2xCPE (R), PVC (U)	30,20	0.75	E	Yes	Comp fill/CPE/G/PVC/CPE/?	No (?)	--

* See text for explanation of terms.

** Comp = compacted; FML = flexible membrane liner; G = gravel; GeoTex = geotextile; Gr = ground; Nat = natural; rk = rock; S = Sand of HDPE which involves a welding process using heat. The other FML materials can be seamed with solvents in the field; the range of thicknesses shown is 10-36 mil. Bottom liner thickness of less than 30 mil would be considered marginally low or too low for a hazardous waste facility that would be permitted under current RCRA rules.

Liner Surface Area

Table 2 shows that the sites selected had liner surface areas ranging from 0.3 to 120 acres. The amount of field seaming required increases as the lined surface area increases. The number of facilities in four size ranges is as follows:

Size	No.
< 1 acre	3
1 - 10 acre	14
11-100 acre	9
>100 acre	1

Exposed vs Buried Liner

This column in Table 2 indicates whether all (or a portion) of the primary liner was left exposed, to wastes or the environment, after installation or were covered with soil (buried). Exposed liners may be susceptible to damage from the environment (wind, sun, waves, ice, hail, heat, cold), animals, vehicles and other factors. Thirteen (13) of the sites had all or part of the primary liner remaining exposed after installation. In some cases (e.g., site V4-4), the exposed sides were to be covered as the landfill height was raised.

Monitoring System

Seventeen (17) of the selected sites had some form of monitoring system designed to allow detection of primary liner failure. The systems involved ranged from simple perimeter drains, to drain systems in double lined facilities, to external monitoring wells. Without such monitoring systems, primary liner leaks are likely to go undetected unless liquid levels (in surface impoundments) drop dramatically or off-site wells are contaminated.

Layers in Liner System

A well-designed liner system, especially one for hazardous waste containment, may contain several layers or elements. Table 2 shows the range of liner systems represented by the sites selected for this study. There is no standard design for a liner system; each site/waste combination must be given special consideration. The use of geotextiles (typically nonwoven, porous fabrics made of polyester or other synthetic fibers) is quickly gaining in popularity today. They can help separate soil layers of different particle size (e.g. sand from gravel), provide a cushion layer next to the FML to help prevent punctures, help in or act as drainage layers and gas venting layers, and act as a lubrication layer next to a FML which may be pulled over the subgrade. Only site V1-1 in our survey reports the use of geotextiles.

Air Vents

Air vents are necessary if a FML is to be left exposed to the air; they help equalize the air pressure above and below the FML and thus prevent lift during windy periods. Some systems require gas vents to allow gases generated under the liner by natural causes (e.g., methane from decomposition of organic matter) to escape. Eight (8) of the sites in this study had some kind of air or gas vent.

SECTION 6

DISCUSSION OF SURVEY FINDINGS

PREVIEW

Section 6 provides an in-depth discussion of the apparent reasons for the "successes" and "failures" noted at the 27 sites evaluated in this study. To a large extent, the discussion is limited to findings from these sites alone, although some generalities (including extracts from the vendors' summary reports) are provided.

The following subsection describes categories of failure in a general way (without reference to the specific sites in this study) in order to set the stage for the subsequent evaluation of actual failures in the third subsection.

The last subsection of Section 6 provides a discussion of the reasons for the successes at the sites studied.

CATEGORIES OF FAILURE

In evaluating lined facility case studies it is important to have a thorough understanding of the various ways in which a liner may fail. First, there is the problem of defining "failure" in a practical manner. In a strict sense, one might limit the scope to ultimate failure of the liner, i.e. events that are directly related to leakage of fluids through the liner. Examples would include punctures, tears, and/or seam failures in critical sections of the liner system.

However, our previous study of liner failures (Lyman et al., 1983) showed that the question of failure mode could be given a much broader definition. The definition encompasses all of the actions and processes that lead to ultimate failure and leakage. This approach thus recognizes various stages of preliminary failure including, for example, poor materials, poor workmanship (especially during liner installation) and poor design. Philosophical failures, relating to a variety of misconceptions (about liners) and motives, were also recognized as being potential forerunners of ultimate failures. A diagram showing such a hierarchy of failure modes is shown in Figure 1. The downward-pointing arrows between boxes in the Figure imply a connection between types of failure, i.e., one type of failure leading to another, a propagation of errors.

There were several examples in the current case study in which an ultimate failure could reasonably be linked (based on the vendor's submission)

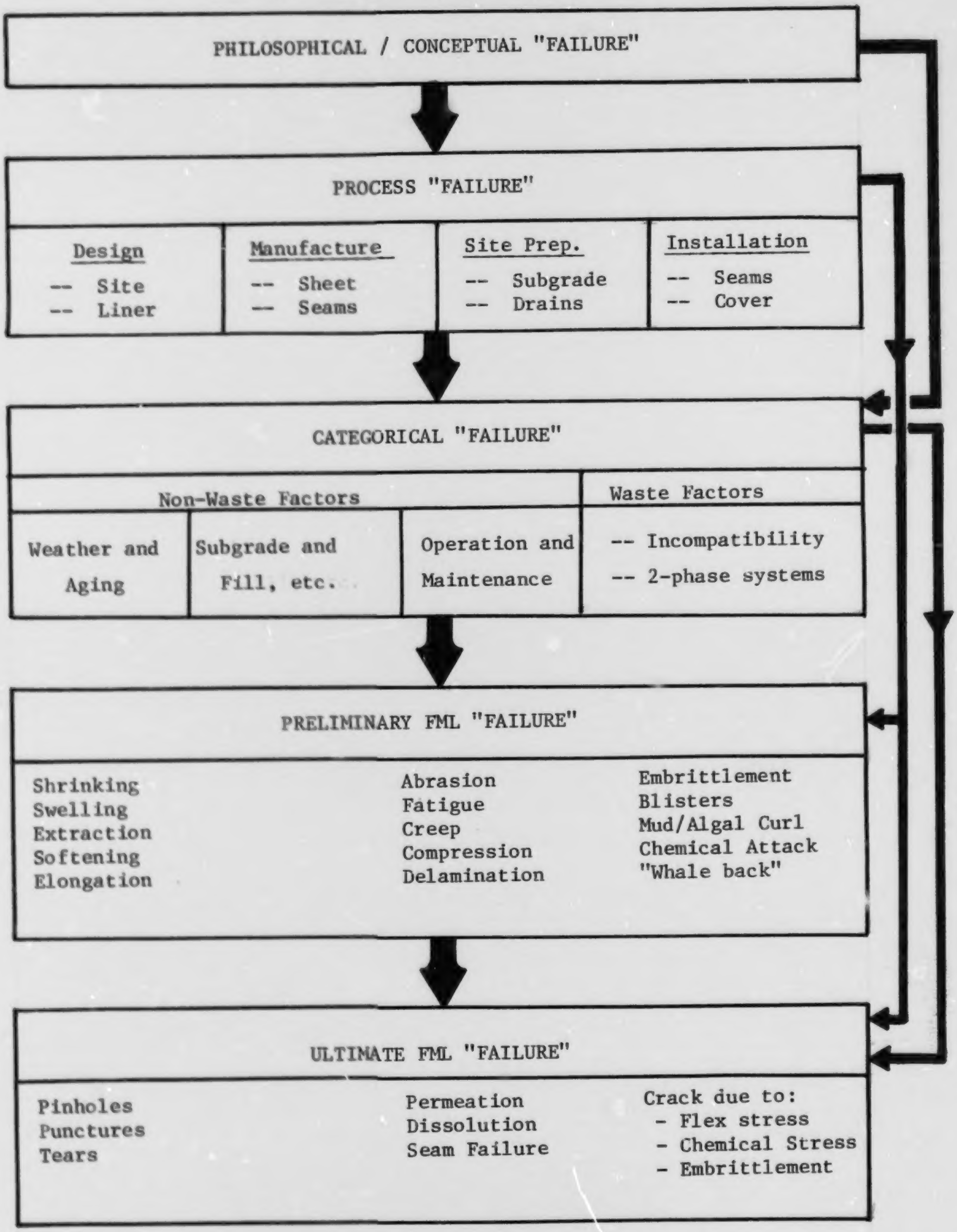

PHILOSOPHICAL / CONCEPTUAL "FAILURE"
PROCESS "FAILURE"
Design
-- Site
-- Liner
Manufacture
-- Sheet
-- Seams
Site Prep.
-- Subgrade
-- Drains
Installation
-- Seams
-- Cover
CATEGORICAL "FAILURE"
Non-Waste Factors
Weather and Aging
Subgrade and Fill, etc.
Operation and Maintenance
Waste Factors
-- Incompatibility
-- 2-phase systems
PRELIMINARY FML "FAILURE"
Shrinking
Swelling
Extraction
Softening
Elongation
Abrasion
Fatigue
Creep
Compression
Delamination
Embrittlement
Blisters
Mud/Algal Curl
Chemical Attack
"Whale back"
ULTIMATE FML "FAILURE"
Pinholes
Punctures
Tears
Permeation
Dissolution
Seam Failure
Crack due to:
- Flex stress
- Chemical Stress
- Embrittlement

Figure 1. Hierarchy of Failure Modes

to prior failure modes. At site V2-1, for example, an ultimate failure reported was the permeation and/or dissolution of the liner at the air-liquid interface of the impoundment. This was attributed to chemical attack (preliminary failure) by an oil-based defoamer discharged to the system without prior evaluation of the possible consequences (operational failure). There may have been conceptual failures here in that the designers and operators of the system were insufficiently sensitive to the need to consider appropriate designs and operational controls that would have prevented the harmful chemical from entering the impoundment in the first place.

Other categorization schemes used in discussion of liner failure modes are shown in Tables 3, 4 and 5. Table 3 shows the scheme used by Kays (1977) in his discussion of cut and fill reservoirs; some of the items listed in this table belong in the "categorical failure" category shown in Figure 1. Kays dedicates a whole chapter of his book to the discussion of liner failure mechanisms; the reader is referred to this work for further information.

Haxo (Matrecon, 1983) provides a different listing of failure modes under the general categories of physical, biological and chemical (Table 4). Haxo's report provides descriptions of all of these mechanisms which will not be repeated here. Haxo's list introduces, beyond those provided in Table 3, failure mechanisms specifically related to chemical factors. For example, a waste (especially liquids containing organic chemicals) may act as a solvent and actually dissolve a flexible membrane liner (FML); weaker solvents may just permeate and swell the liner.

Woodward-Clyde (1984) used the scheme shown in Table 5 in their evaluation of liner site case histories. Of these, seaming (a subheading under defective installation) was found to be the most frequent problem area.

In the current study, no rigid classification scheme for failures was used (or really needed). However, two general types of failure that were differentiated were:

1). Failure before operation: This is defined as a condition of the liner which required non-routine corrective measures to make the liner suitable for use as designated. (e.g., tear or puncture caused by construction equipment)

2). Failure during operation: This is defined as a condition of the liner which causes (or threatens to cause) groundwater contamination, or which otherwise causes operations to cease because of observed abnormalities (e.g., "whale-backs," algal curl, preliminary chemical attack).

Success is defined as the converse of failure, i.e., non-routine corrective measures are not required, the liner does not leak, and operations are not shut down.

Identifying the reasons for specific liner failures, and categorizing them according to some scheme, is not particularly difficult since there is usually a specific happening (e.g., a tear) for which certain facts and causes

TABLE 3 CLASSIFICATION OF THE PRINCIPAL FAILURE MECHANISMS FOR CUT-AND-FILL RESERVOIRS

Supporting structure problems

- The underdrains
- The substrate
  - Compaction
  - Texture
  - Voids

  - Subsidence
  - Holes and cracks
  - Groundwater
  - Expansive clays
  - Gassing
  - Sluffing
  - Slope anchor stability
  - Mud
  - Frozen ground and ice
- The appurtenances

Lining problems

- Mechanical difficulties
  - Field seams
  - Fish mouths
  - Structure seals
  - Bridging
- Porosity
- Holes
- Pinholes
- Tear strength
- Tensile strength
- Extrusion and Extension
- Rodents, other animals, and birds
- Insects
- Weed growths

- Weather
  - General weathering
  - Wind
  - Ozone
  - Wave erosion
  - Seismic activity

Operating Problems

- Cavitation
- Impingement
- Maintenance cleaning
- Reverse hydrostatic uplift
- Vandalism

Source: Kays (1977)

TABLE 4 FAILURE CATEGORIES

Physical	Biological	Chemical
Puncture	Microbial attack	Ultraviolet attack
Tear		Ozone attack
Creep		Hydrolysis
Freeze-thaw cracking		Ionic species attack
Wet-dry cracking		Extraction
Differential settling		Ionic species incompatibility
Thermal stress		Solvents
Hydrostatic pressure		
Abrasion		

Source: Matrecon (1982)

TABLE 5. FAILURE MECHANISMS OF IMPOUNDMENTS LINED WITH GEOMEMBRANES

- Failure of Geomembrane
  - Manufacturing defects
  - Weathering
  - Physical
  - Chemical
  - Mechanical
- Defective Installation
  - Storage
  - Transportation
  - Placement
  - Seaming
  - Appurtenances
  - Placement of cover materials
- Damage by Contact
  - Puncture
  - Vegetation
  - Shocks
- Gas and Liquid Damage
  - Gas uplift
  - Wind
  - Waves
  - Liquid uplift
  - Overtopping
- Geotechnical Problems
  - Slope instability
  - Sloughing of cover material
  - Subsidence
  - Differential settlement
  - Expansive clays
- Other Failure Mechanisms
  - Vandalism
  - Seismic activity

Source: Woodward-Clyde (1984)

may be quite evident. By contrast, identifying the reasons for success is more difficult since there is an absence of any specific, adverse event. In a simple manner, the reasons will often be directly associated with steps that were taken to prevent problems, or to identify and correct problems as they arise. These steps will be part of a quality control system, although the liner manufacturer, installer and user may not use this exact phrase. These quality control steps are any actions based upon the premises that problems and/or mistakes can occur, and that reasonable steps must be taken to prevent and/or correct problems when they occur.

EVALUATION OF FAILURES AT STUDY SITES

There were twelve problems, at ten sites, described in the vendors' reports that fit the definition of "failure" described in the previous subsection. Table 6 provides a summary description of these failures and the apparent reasons for them based on the data in the vendor reports. As a consequence of these failures, pollutants were apparently released to the environment (i.e., the soil-groundwater system under the site) at four or five sites (V1-2, V3-1, V3-2, V3-4 and V5-4), and one site was permanently removed from service (V2-2).

The following observations are made with respect to these failures:

1. Pre- vs post-operational and Detection: At three sites, (V2-3, V3-1 and V5-2) the failures were pre-operational; all were detected visually. At the other seven sites (V1-2, V2-1, V2-2, V3-2, V3-4, V5-1, and V5-4) the failure was noted in the operational phase of the site; detection of failure was predominantly by monitoring well or leak detection system (5 sites) vs visual observation (2 sites). However, of those sites where failures were noted in the operational phase, it is likely that four of them were related to "preliminary" failures (e.g., inadequacies in design or installation) in the pre-operational phase (sites V2-2, V3-2, V3-4, and V5-4). Poor control of operations was a contributing factor at three sites (V1-2, V2-1 and V3-1).

2. Nature of "Failure":

(a) Chemical attack - present at site V2-1, possible at site V3-4;
(b) Physical tear or puncture - a cause at five sites (V1-2, V2-3, V3-1 (twice), V5-2 and V5-4);
(c) Poor installation or seaming: present at site V3-2, possible at sites V3-4 and V5-1; problems during installation were also a contributing factor at 3 other sites (V3-1, V5-2 and V5-4);
(d) Whale-backs - present at site V2-2.

3. Weather as a Factor: Of the sites that had "failures", poor weather was a probable contributing factor at two (V3-1 and V5-2). In addition, three other sites that did not report any failures (V4-2, V4-4, and V4-5) mentioned weather as an adverse factor during installation. Altogether, weather was an adverse factor at 5 of the 27 sites.

TABLE 6. SUMMARY DESCRIPTION OF "FAILURES" AT CASE STUDY SITES

Site ID	Nature of "Failure"	How Detected	Apparent Cause	Other Contributing Factors
V1-2	Five holes found in liner caused by owner-operating personnel; minor brine loss	Monitoring well	Carelessness by owner-operating personnel	- Lack of clear operating procedures. - Possible lack of concern (speculative).
V2-1	Chemical attack of liner at liquid surface	Visual	Attack or dissolution by oil-based defoamer	- Use of oil-based defoamer not anticipated, thus not in original test program. - Inadequate control of operations.
V2-2	Whale-backs	Visual	Gas generation under liner; no allowance made for gas venting in design	- Inadequate study of soils and hydrogeology at site; presence of organic matter (in soil) had, however, been noted. - Site used before for disposal of organic sludges.
V2-3	Liner ripped	Visual	Tank truck slipped down slope	- No fence around site. - Liner exposed.
V3-1	a) Holes and tears in liner	Visual	Liner placed betweeen layers of coarse rock	- Poor design.
	b) Escape of dredge material	Visual	Liner placed over coarse rock	- Poor control of operations. - Poor communication between contractor, installer and engineer. - Job awarded to low bidder (speculative).
	c) Tear in liner panel	Visual	Waves entered construction area and scraped liner against dike	- Poor design (subgrade too coarse). - Poor control during installation. - Wet and windy weather.
V3-2	Chemical pollutants showed up in drain water collected below liner	Leak Monitor	Apparent blockage of leachate collection drain; backup of leachate	- Poor bonding at seams, appurtenance (?). - Poor control of installation practices; used "Honor Camp" youth to install FML - Undersized collection drain (?); due to poor design (?).

(Continued)

TABLE 6. SUMMARY DESCRIPTION OF "FAILURES" AT CASE STUDY SITES (continued)

Site ID	Nature of "Failure"	How Detected	Apparent Cause	Other Contributing Factors
V3-4	Pollutants showed up in monitoring wells around site	Monitoring well	Unknown; possible breakup of soil sealant liner	- Unknown; possible failure to fully test soil sealant for this type of application - Process for selecting liner unclear. - No way to physically test liner once in use.
V5-1	Liquids found in leak detector	Leak detector	Probable failure of sealing of concrete joints with PVC strips and spray-on liner, CIM	- Concrete installer, against explicit instructions, used curing compound that inhibited proper bonding of CIM to concrete. - Poor design: improper information supplied on CIM; owner suggested use of CIM. - Poor installation: lack of knowledgeable supervision.
V5-2	Physical damage to liner prior to being put into service	Visual	Unknown, but suspect carelessness	- Questionable cooperation between contractors. - Job awarded to low bidder (speculative). - High winds and cold temperatures during construction (took 11 months).
V5-4	Fluid intrusion into monitoring well	Monitoring Well	Membrane rupture at five, uniformly-spaced positions; tears probably by D-4 cat tractor used to spread soil cover over liner	- Operator of tractor let soil cover get too thin. - Poor control of installation.

4. Construction in Old Dump Site Areas - The failure at one site (V2-2) was clearly related to the use of an old dump site for the new lined facility. The ground was contaminated with organics and had a high water table; gas generated by the decay of the organic matter was trapped below the liner and resulted in the "whale-backs". Two other sites (V2-4 and V5-3) were also constructed in areas with contaminated soils although no subsequent problems were noted. None of the three sites had gas vents.

5. Waste-Liner Compatibility Testing: Waste-liner compatibility testing appears to have been conducted for only four sites (V2-2, V2-4, V3-4 and V2-1[?]). As noted in #2 above, chemical attack was possibly responsible for the failure at site V3-4; thus, there may have been some inadequacies in the tests conducted. At a number of other sites the liner (or resin) manufacture provided assurances of compatibility based upon past experience or in-house data (sites V1-1, V2-3, V5-2, V5-3, V5-4, V5-5).

Other problems noted by the vendors, not all of which were connected with sites which had "failures", included the following:

- Installer had difficulty placing liner over geotextile fabric (V1-1);
- Inability to easily test degree of soil compaction in field (V1-3);
- Failure to conduct waste-liner compatibility tests (various sites);
- Indications that constructed facilities might be used for unplanned uses (thus not anticipated in the design) (V1-5);
- Gas generation between limestone and effluent; careful venting required (V2-1);
- Difficulty in repairing aged liner material (V2-1);
- Inadequate corrective measures taken due to desire for cheap solution (V2-2);
- One vendor reported problems with asphalt cracking (at other sites) in response to freeze-thaw cycles (see V3-5 data);
- Earthwork contractor had to be removed from job due to poor work (V4-2);
- Differential settlement in subgrade caused initial clay liner to crack (V4-5);
- Mud and water in site caused difficulty in welding seams (V4-7).

Discussion of Special Issues

Untrained Installers --

The use of untrained installers was evident at several sites. Apparently the site owners or general contractors see this as one easy place to control costs by using low wage earners or, as in the case of sites V2-3 and V3-4, using employees of the site owner. The vendors' responses to question V.C.6 of the questionnaire indicate that, in their opinion, the installers were not qualified at three sites (V2-2, V3-2 and V5-1 [for the CIM]), and that at an additional five sites (V2-1, V2-3, V2-4, V3-1 and V3-3) only the installation supervisor(s) was(were) qualified.

Independent Design Engineer --

According to the vendors' responses, for 13 of the 27 sites the site owner acted as the design engineer: V1-5, V1-6, V2-1, V2-2, V2-4, V3-1, V3-2, V4-2, V4-3, V4-5, V4-6, V5-4, and V5-5 (the underlined sites are recorded as having failures). This apparent failure by nearly half the sites to use independent (and presumably qualified and certified) design engineers is a cause for concern. (It is possible that some of the owner-designers used outside consultants or design engineers without the knowledge of our vendors.)

Number of Companies Involved in Site Work --

The number of independent companies involved in the design, manufacture and installation of each lined site ranged from 4 to 8; Figure 2 provides a histogram showing the breakdown. These companies play several roles as shown in Figure 3. The interaction between all these companies, the site owner and the regulatory agencies is a potential problem area. Although communication or cooperation problems were only mentioned for two sites (V3-1 and V5-2), there are many places for problems to arise when so many interests are involved. Who, for example, has overall responsibility for quality control? Who provides what warranties to whom? How reliable is each component; How important is it to use a "team" of companies that has worked together in the past?

Process for Selecting Companies --

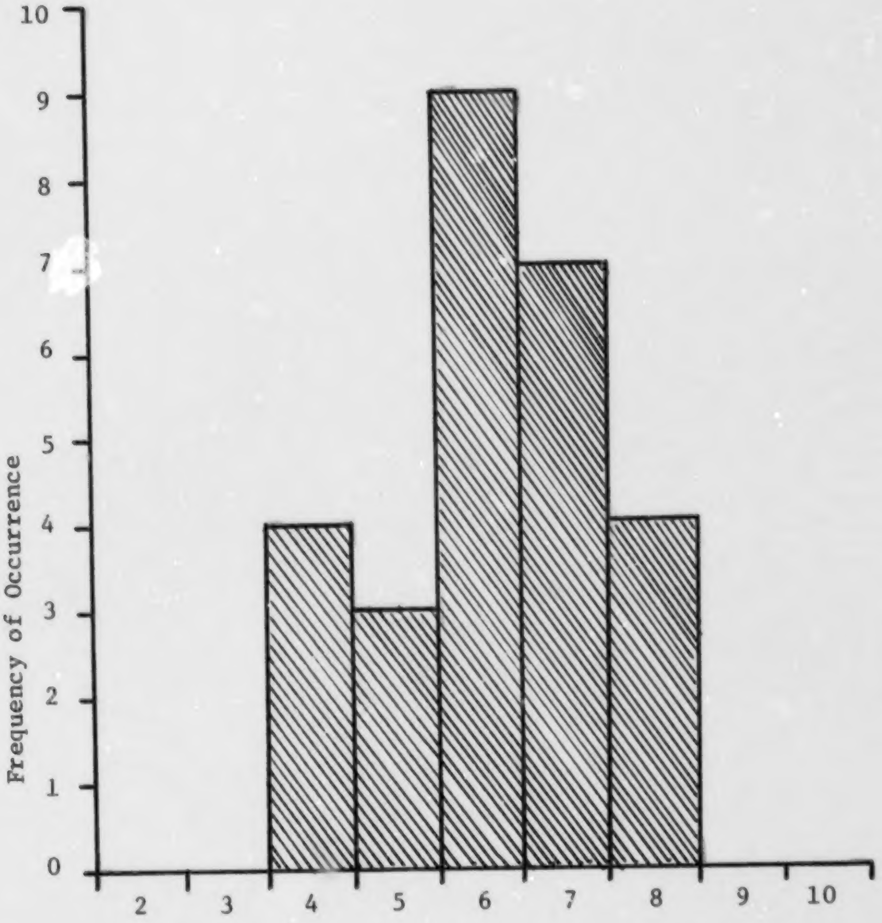
It appears that a bidding process was used at eleven or more sites as part of the contractor, liner manufacturer, and liner installer selection process. Furthermore, it appears that low price was the deciding factor in the selection at about seven of these sites. Whether or not these low bidders all proposed to adequately meet a set of bid specifications is not known. The degree of detail and quality of any bid specification package is also not known. This emphasis on low cost is understandable, but is an area for concern if it appears that liner quality is being sacrificed.

In the cases where a bid process was not used, the selection often focused on: the special qualities of an established team (manufacturer/fabricator/installer); prior experience of the company(ies) with the site owner; prior experience related to the type of installation being built; selection by an existing on-site contractor; and, in one case, the properties of the liner material being sold (HDPE).

Process for Selecting Liner Material--

It appears that liner specifications were prepared for between 11 and 16 of the sites studied, either by the design engineer, a consultant, or the owner. In at least eight instances, the vendors' responses made it clear that such specifications were used in conjunction with the solicitation of competitive bids. (A bid process was involved for at least 5 other sites, but the basis for the bids could not be ascertained from the vendors' responses.) The eleven sites were: V1-1, V1-4, V1-5, V2-4, V4-2, V4-3, V4-4, V4-7, V5-2, V5-3, and V5-4; other possibilities were V2-2, V2-3, V3-2, V3-5 and V5-5 (underlined sites reported as having "failures").

It is important that liner selection follow from a process that includes: (1) the preparation of detailed specifications by a qualified design engineer;



Number of Companies Involved in Liner Design/
Manufacture/Installation

(Note: Count includes only major principals; excludes raw materials suppliers [except for resin manufacturer] and independent testing laboratories.)

Figure 2. Frequency Distribution of Number of Companies Involved In Liner Installation Jobs.

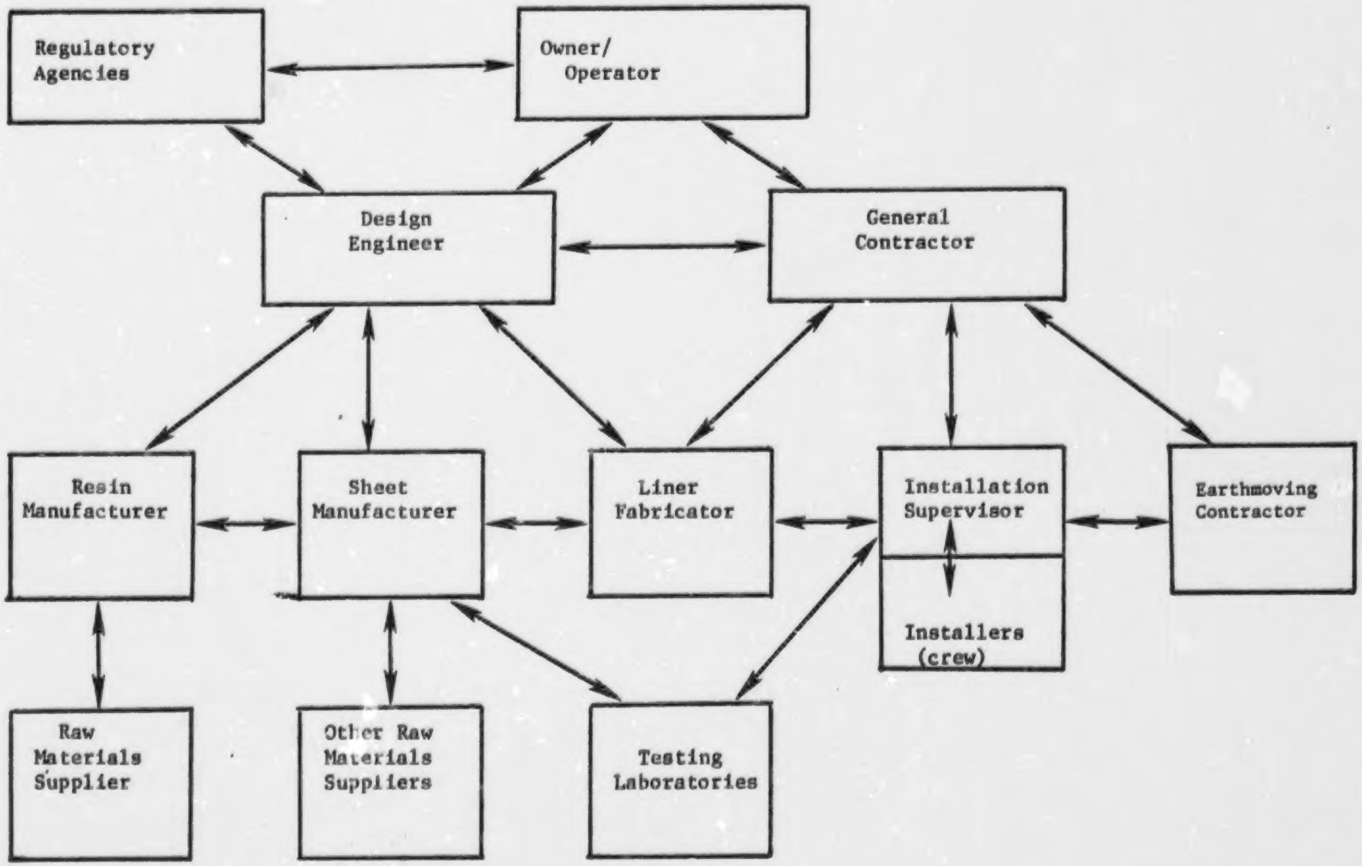

Regulatory Agencies
Owner/ Operator
Design Engineer
General Contractor
Resin Manufacturer
Sheet Manufacturer
Liner Fabricator
Installation Supervisor
Installers (crew)
Earthmoving Contractor
Raw Materials Supplier
Other Raw Materials Suppliers
Testing Laboratories

Figure 3. Schematic Diagram (Hypothetical) of Interaction Between Groups or Companies Involved in a FML Installation Job.

and (2) bids by companies who promise to meet those specifications. (Waste-liner compatibility testing is also required, at least as a confirmatory step.) At the 10 (or more) sites where such a process was apparently not used, there is cause for concern with regard to the appropriateness of the liner that was selected. Vendors' responses indicated that "prior history", general contractor preference, owner preference, and informal interviews were the basis for liner selection in some of these other cases.

Facility Age--

It is not clear that failures correlated with facility age in the sites studied although, as seen in Figure 4, there were failures at 3 of the oldest facilities, and at 7 of the 10 facilities installed prior to 1980. It is possible that this higher tendency for failures at older sites can be attributed: (1) to the (assumed) use of less appropriate designs, materials and installation practices at older sites; (2) to the (assumed) paucity of related experience by the manufacturing and installing companies in those early years; and/or (3) just to the fact that there has been more time for failures to show up.

Facility Size --

Facility size correlates with failure rate in our selection of sites although the significance of this correlation is unclear. As shown in Figure 5, there were noted failures at both large and small facilities. If, however, it is assumed that vendor V4 had a bias against selection of problem sites (no failures were noted at any of the 7 sites selected for this study), and the V4 sites are not considered in the facility size/failure correlation, then all 5 (5 of 7 including V4) sites larger than 20 acres had failures and 7 of the 10 (7 of 15 including V4) sites greater than 6 acres had failures. While a strong correlation may not be a general rule, the necessity for added planning, care, quality control, etc. with large facilities is fairly evident.

Monitoring Systems --

Seventeen (17) of the 27 sites had some form of monitoring system to detect failures in the primary liner. Figures 4 and 5 indicate the sites with monitoring. Seven of the sites with monitoring systems had failures, but, as noted above (see Table 6), the monitoring system was involved in the identification of the failure at only 5 sites. Still, it is possible that if our vendors had selected a higher percentage of sites with monitoring systems, more failures might have been identified. In any case, the necessity for some type of monitoring system at RCRA-permitted sites is quite clear.

Field Seam Repairs --

According to the vendors' reports, all field seams were checked for integrity. (Only sites V3-4 and V3-5 which did not use FMLs are excluded.) In most cases the vendors explicity said 100% of the seams were checked by one or more means, e.g., visual, air lance, feeler gauge or ultrasonic device. However, the adequacy of the inspection can be questioned in several cases. Apparently only visual inspection was used at sites V3-2 and V3-3; and at sites V5-2, V5-3, V5-4 and V5-5 only visual plus feeler gauge inspection was used. No details were provided on the inspection methods used at some sites (e.g., V5-1).

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FIGURE 4

Figure 4

center → CORRELATION OF FACILITY AGE WITH FAILURES

Correlation of Facility Age with Failures

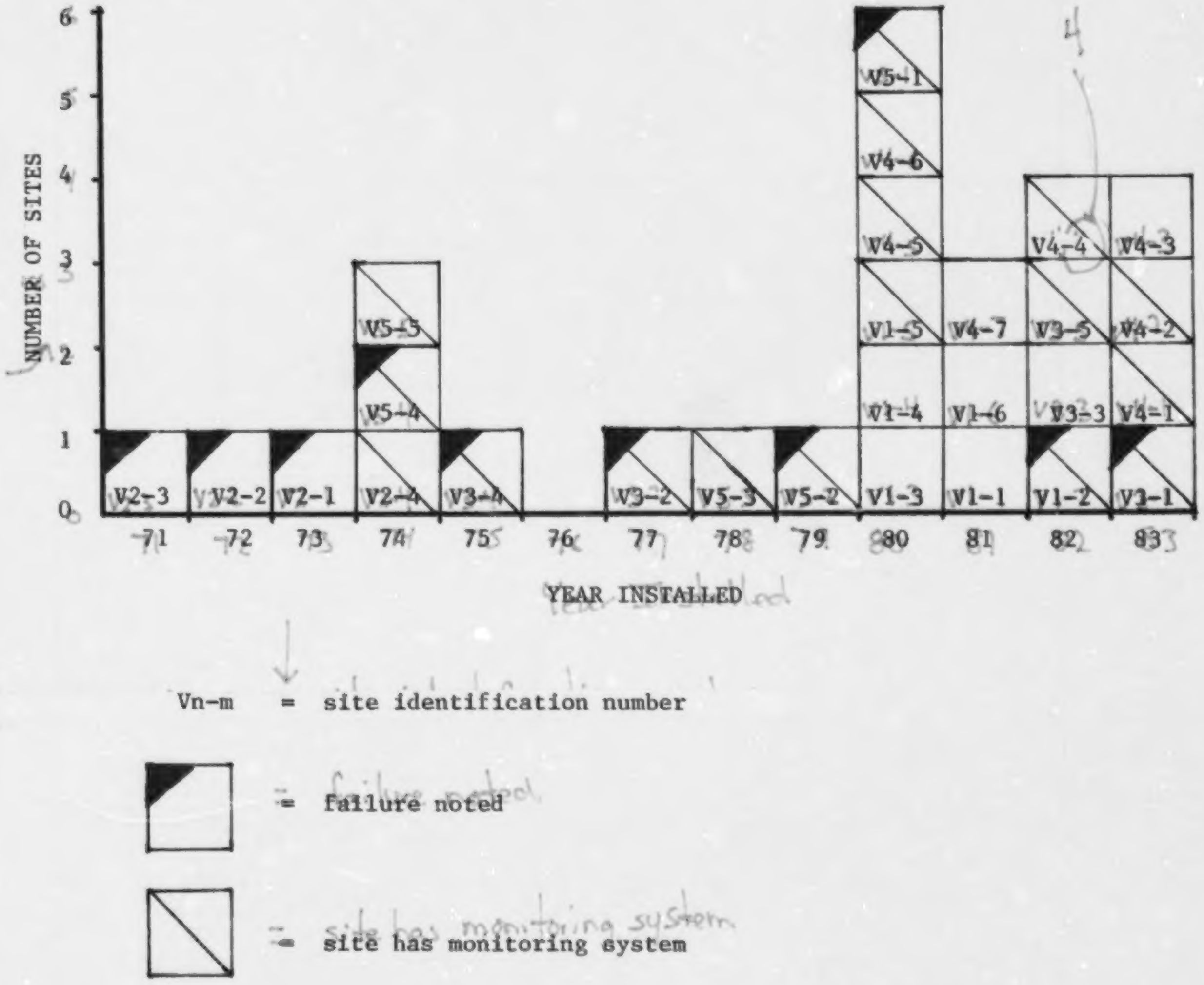

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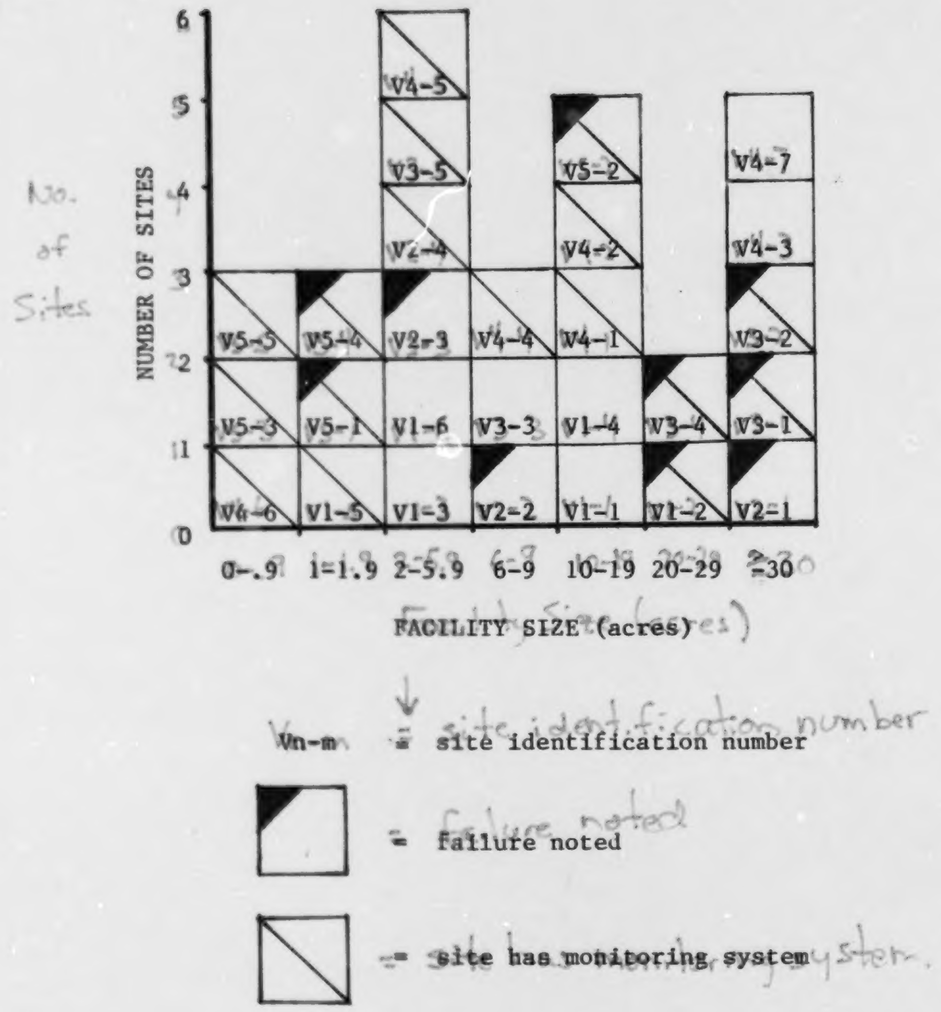
Figure 5

FIGURE 5

center →

CORRELATION OF FACILITY SIZE WITH FAILURES

Correlation of Facility Size with Failures



The vendors' experience showed that repairs were generally necessary on 0.5% to 2% of the seams (by length). At one site it was 8% (V4-4). These data indicate that 100% checking of field seams is clearly necessary.

Vendors Comments on Causes for Failures

The coded summary reports from the five vendors are provided in Appendix B. They contain discussions of causes for liner failures based upon the vendors' overall experience. Extracts from their summaries are provided below.

Vendor V1 --

[See comments under discussion of success in the following subsection]

Vendor V2 --

[Comments limited to specific sites studied; See Appendix B]

Vendor V3 --

Causes for liner failures include:

- Inadequate pre-selection testing of the liner
- Inadequate quality assurance programs
- Inadequate leachate control systems above the membrane liner
- Liner contact with poorly selected and placed gravel drains
- Use of heavy construction equipment
- Leakage around vertical risers
- Ineffective membrane seams.

Vendor V4 --

Causes for liner failures include:

- Chemical incompatibility
- Low mechanical strength resulting in poor tear and puncture resistance
- Poor seaming
- Soil conditions (compactability, stability, etc.) play an important role
- Failure to conduct waste-liner compatibility testing.

Vendor V5 --

- In almost all cases, failures have been mechanical in nature
- Reservoir level management a cause in one case
- Ultraviolet attack has caused several failures for exposed liners
- One failure linked to improper compounding of resin for liner.

EVALUATION OF SUCCESSES AT STUDY SITES

Introduction

In a previous subsection, success was defined as the converse of failure, i.e. non-routine corrective measures were not required, the liner did not leak, and operations were not shut down.* Using this strict definition, seventeen of the study sites were considered successes as of the time of data collection (late 1983).

However, it also seems fair to broaden the definition of success to include sites where problems did occur but were identified and corrected without any attendant release of pollutants to the environment. This would allow sites V2-1, V2-3, V5-2 and V5-1 to be considered qualified successes. (Site V5-1 did release pollutants through its primary liner, but they were detected in a leak detection system.) Thus, a modified success rate of 21 of the 27 sites might be cited. This would have to be qualified with the caution that not all failures may have been identified at each site, and that failures could occur in the future at any of these sites.

Finding the reasons for success is more difficult than finding the reasons for failure. Since success is the absence of failure, it is essentially asking why everything went right. Clearly, no one action can be credited with a resulting success as, by contrast, it could for a failure. More commonly, success will follow from an understanding of the potential problems associated with liner installation and use, and the subsequent planning to avoid as many problems as can reasonably be perceived in advance, and to quickly identify and correct other problems as they arise.

Comments on Reasons for Success at Individual Sites

Table 7 lists a number of specific comments on success for 23 of the 27 sites where either the vendors made a pertinent comment or where some other comment seemed appropriate. This part of the site questionnaire (i.e., Section IX of questionnaire) did appear to attract a number of self-serving statements by the vendors. These have been placed in quotes in Table 7.

Vendor Comments on Causes for Success

The summary reports from the five vendors are provided verbatim in Appendix B. They contain discussions of causes for liner successes based upon the vendors overall experience. Extracts from their summaries are provided below.

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* This report is based only on the data reported to us by the five vendors. No attempt was made to estimate how many "failures", of what severity, existing or in the future, may remain undetected.

TABLE 7. COMMENTS ON REASONS FOR SUCCESS AT INDIVIDUAL SITES

Site ID	Comments (by Vendor* or A. D. Little, Inc.)
V1-1	- Overdesign of liner system - Not a difficult job; no chemicals of concern - Used geotextiles, soil cement
V1-2	- After holes repaired, "proper education of engineer and owner" led to success - Not a difficult job - Established team used - Standards imposed by State Railroad Commission - Good design
V1-3	- "Excellent construction weather and coordination of all principals involved" - "Good design and proper installation" - Prior history of similar application
V1-4	- "Quality PVC specified, proper design engineering, and a quality installation" - Used established team - Bid to specs of design engineer; bids reviewed by design engineer
V1-5	- "Quality lining system properly designed and installed" - Knowledgeable customer - Bid to specs
V1-6	- "Designed and installed with good fundamental engineering practices, and competent and experienced installation personnel" - Established team - Knowledgeable customer
V2-1	- Problem (of chemical attack) solved by switching to non-oil-based defoamer - Repairs to liner include installation of cover strip at liquid level
V2-2	- [None identified]

(Continued)

TABLE 7. COMMENTS ON REASONS FOR SUCCESS AT INDIVIDUAL SITES (continued)

Site ID	Comments (by Vendor* or A. D. Little, Inc.)
V2-3	- Close cooperation between all parties that installed liner
V2-4	- Knowledgeable owner - Close liason by companies on installation - Site study of soils, hydrology - Waste-liner compatibility tests conducted
V3-1	- Site study done
V3-2	- [None identified]
V3-3	- Reasonable level of care in design and work
V3-4	- [None identified]
V3-5	- [None identified]
V4-1	- "Thickness, puncture resistance and chemical resistance of liner" - Relatively few companies involved - Relatively standard installation
V4-2	- "Thickness, puncture resistance and chemical resistance of liner" - Relatively few companies involved - Some care given to design
V4-3	- "Thickness, puncture resistance and chemical resistance of liner" - Relatively few companies involved - Some care given to design - Past experience (?)
V4-4	- "Thickness, puncture resistance and chemical resistance of liner" - Relatively few companies involved - Some care given to design

(Continued)

TABLE 7. COMMENTS ON REASONS FOR SUCCESS AT INDIVIDUAL SITES (continued)

Site ID	Comments (by Vendor* or A. D. Little, Inc.)
V4-5	- "Thickness, puncture resistance and chemical resistance of liner" - Some care given to design
V4-6	- Relatively few companies involved
V4-7	- "Thickness, puncture resistance and chemical resistance of liner" - Some care given to design - Simple system
V5-1	- CPE performed well
V5-2	- Liner repaired satisfactorily and now functions successfully
V5-3	- Good cooperation of companies on team
V5-4	- Good cooperation amongst companies - Relatively simple system - Good design (?)
V5-5	- Knowledgeable owner (?) - Regulatory intervention (?) - Good weather (?) - Good cooperation amongst companies

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* Comments in quotes are by vendor and appear partially self-serving. Quotes may not use exact wording of vendors, but are reasonably close.

Vendor V1 --

The key elements of a successful liner system are:

- Proper design engineering
- Proper material selection
- Proper earthwork preparation
- Proper lining installation
- Proper maintenance of the lining system

Vendor V2 --

[Comments limited to specific sites studied; see Appendix B.]

Vendor V3 --

In general, the successful installations are those with the least complex design, and having an "as-built" condition most similar to the design plans.

Vendor V4 --

Need more focus on:

- Liner material (especially chemical compatibility)
- Puncture resistance
- Seaming (good technique, good quality control program).

Vendor V5 --

Use of double lined system.

Synthesis

In providing a synthesis and independent evaluation of the apparent reasons for success at the study sites, we have developed several hypotheses which we believe are reasonable and consistent with the cases actually studied. There is, however, no way to prove the hypotheses based on the data gathered for these sites, but future case studies could be used to test them.

First, success is more likely to follow if the responsible individuals have the proper philosophical and conceptual approach (cf. Figure 1). If they understand that what they are doing is important and that the process of designing, installing and using a lined facility involves many technical factors that will likely present problems, then they are more likely to proceed with due diligence. A key element of the proper philosophical approach is indeed: (1) to assume that there will be problems; (2) to examine the possible consequences of those problems and/or "failures"; and then (3) to take the appropriate steps (e.g., design changes, quality control procedures) to avoid or minimize the problems.

Second, this approach must be applied to all stages or facets of the liner system including:

- Liner system design
- Liner material selection
- Site preparation
- Liner installation
- Facility operation (including liner maintenance)
- Facility closure (for RCRA landfills requiring covers)

Within each of these areas, the generalized approach must be applied within the framework of a formal quality assurance (QA) program. It is worth noting that the vendors reported that at least 23 of the 27 sites had some sort of a quality assurance program[*] ; no data were provided on the other four sites. It is difficult to judge

the coverage of the QA programs used in the study sites, but about 17 sites (each) specifically mentioned the use of a QA program for: (a) liner manufacture, (b) liner fabrication; and (c) liner installation. If a detailed QA program were developed and followed for each of the steps listed above, the "success" rate would likely be increased.

Finally, there are a number of more specific items that appear to be related to success and deserve special mention even if they are partly covered by good QA programs.

Overdesign --

In the face of uncertainty, it is always possible to add an extra margin of safety by overdesigning a liner system. This might involve the use of an extra (2nd or 3rd) impermeable layer, an extra thick FML, judicious use of geotextiles above and below FML, extra protective soil or sand cover over FML, etc.

Knowledgeable Customer --

Several vendor reports mentioned that the presence of a knowledgeable customer was a significant factor in the success. Perhaps this should be a warning to site owners not to place complete faith in their design engineer or general contractor (etc.) since the latter may, if given the motive and opportunity, put their own self interests ahead of the site owner's. If owners completely abrogate themselves from any oversight role or responsibility in a liner job, or show ignorance about the basics of liner systems, then they may - intentionally or not - be taken advantage of. A liner system prone to failure could easily res[illegible].

Bidding to Specifications --

Additional assurances of success will come if, at key stages (e.g., FML material selection, earthwork preparation, FML installation), detailed specifications are prepared by independent, qualified engineers, and then companies are requested to submit bids for work which will meet these specifications. If, by default or otherwise, a company is chosen by some other method, and the job specifications lack detail or reflect the vendor's standard 'product' specifications, then an inadequate system may result.

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[*] Based on response to question V.C.7 of questionnaire.

Obviously, any quality assurance program used should involve steps that ensure that the products and services purchased for the liner system meet the agreed-upon specifications.

Selection of Qualified Companies --
In spite of the obviousness of this statement (i.e., the need to select qualified companies for the liner job), there can be much controversy over the means by which experience and reputation are judged. Simple yardsticks using years of experience and total square feet (of FML) installed might be used in conjunction with references and an examination of the company's financial stability. Most important might be one or more good references relating to performance in similar types of jobs. Care must be taken that such criteria do not unfairly exclude smaller, newer companies (which may have been started by very experienced employees from established firms) which may be willing to offer more attractive prices or services. General reputation, past performance and financial assets are a better indication than the type or duration of warranty of a company's willingness and ability to correct obvious defects related to poor materials and workmanship.

Cooperation Amongst All Parties --
As noted earlier in this section, it is common for five to eight companies - excluding the site owner - to be involved in the design and construction of a lined impoundment. Good coordination and cooperation amongst these companies can help ensure success. Situations where one company takes on (adequately) more than one role, e.g., as manufacturer fabricator and installer of the FML, clearly appear more attractive in this regard since less inter-company interaction is required. Perhaps equally attractive are teams of companies, e.g., a resin manufacture, sheet maker and fabricator, who have demonstrated by past examples that they can work well together. Both of these situations exist in the current FML market place.

Waste-Liner Compatibility Testing --
Proper evaluation of the compatibility of the waste (or leachate) with the liner material is crucial if assurances of long-term containment are desired. These tests, at a minimum, must evaluate the change in physical properties (dimensions, weight, strength, elongation, etc.) as a function of time for at least four months. (Shorter tests may be used in an initial screening process to select a FML for confirmatory tests.) Unfortunately, there is at present no agreed-upon way to interpret the data from these tests so that "acceptable" and "unacceptable" liners can be simply identified.

Use of Geotextiles --
It is becoming increasingly evident that geotextiles, nonwoven mats of porous fabric, can play a variety of beneficial roles in liner systems. They can act as a cushion and lubricant under an FML (providing protection against pinholes as well as assisting in gas venting), as a separator between layers of different particle size, and as a stabilizer under loadbearing dirt layers (e.g., ones that must bear truck traffic.

Simplicity of Design --
More than one vendor mentioned simplicity (i.e., of liner site design) as a factor in success. This would presumably include, for example, keeping the

number of appurtenences (around which a FML must be laid) small, and keeping their size small and the shape simple.

Good Weather --

Having good weather for site preparation and FML installation need not be completely a matter of luck. First, the appropriate season (dry, warm) can be selected for such work. Second, clear rules can be agreed upon in advance between the site workers and the owner (or general contractor) that no work be done on days when wind, precipitation, temperature or soil moisture values fall outside set limits.

SECTION 7

RECOMMENDATIONS FOR FUTURE RESEARCH

RECOMMENDATIONS SUGGESTED BY PROBLEMS AT SPECIFIC SITES

Table 8 provides a listing of research topics suggested either directly by the vendors or indirectly by the information they supplied based on problems noted at individual sites. Of the 15 topics listed, ten are recommendations for additional guidance documents on a variety of subjects such as the use of geotextiles, TSDF operations to safeguard liners, and design of drain systems for TSDFs. Some of these subjects are covered, in whole or in part, by EPA reports currently available or in preparation.

Three of the recommendations in Table 8 relate to the need for much more information on the use of soil sealants (e.g., soil cement), spray-on membranes, asphalt and concrete as integral parts of liner systems. Although the current RCRA regulations look more favorably on FMLs (at least for landfills), there may be many instances where these other products might provide a valuable component of a liner system.

VENDORS COMMENTS ON RECOMMENDED RESEARCH

The summary reports of the five vendors are provided in Appendix B. Two contain recommendations for future work based upon the vendor's overall experience in addition to the recommendations based on their experience at the specific sites used in this study. Extracts from their summaries are provided below.

Vendor V1

- Determine consistent quality standards for membrane liner materials; test protocols would also have to be revised and standardized.

Vendor V3

- Need a study of [field] seaming techniques that would evaluate effectiveness of various techniques for various membrane materials; other variables in study would be application environment, waste characteristics, budget requirements; seaming techniques to include welding, solvent bonding, double seaming, overlap seams, etc.
- Develop improved methodologies for estimating the rate of leachate movement through waste disposal facilities.

TABLE 8 RESEARCH TOPICS SUGGESTED BY SPECIFIC SITES

Site		Suggested Research Topic
V1-1	-	Use of geotextiles at lined impoundments; prepare Technical Resource Document that describes materials, ways to use, benefits, problems, etc.
V1-2, V2-1	-	Guidance document for operating procedures at TSDFs focusing on steps necessary to protect (and check the integrity of) the liner. Include discussion of pretreatment of wastes to eliminate liquids that may attack liner.
V1-3	-	Need to develop simple field test to determine if soil adequately compacted [and dried] for subsequent field seaming of FML without use of boards (under seam).
V1-4	-	Prepare guidelines on how to write bid specifications for liner system.
V1-5	-	[None]
V1-6	-	Possible need for special guidance in selection of FMLs to be used as caps.
V2-2	-	Provide guidance on methods to evaluate potential for gas generation in subsoils.
V2-2, V2-4	-	Provide guidance on acceptability of using old dump sites for new TSDFs.
V2-3	-	[None]
V3-1	-	Provide guidance on how to get (ensure ?) proper coordination and cooperation between different companies on liner job.
V3-1	-	Provide specifications for subgrade materials that are acceptable for base material under FMLs.
V3-2	-	Prepare design manual covering hydraulics of leachate collection, proper drain design, materials, construction methods, etc. Discuss causes of drain failure, remedial action alternatives.

(Continued)

TABLE 8 RESEARCH TOPICS SUGGESTED BY SPECIFIC SITES (continued)

Site		Suggested Research Topic
V3-2	-	Provide guidance on best ways to seal FMLs around appurtenances.
V3-3	-	[None].
V3-4	-	Obtain more information (of all types) on soil sealants: materials, use, experience (more case histories), problems, etc.
V3-5	-	Obtain more information (via case histories) on asphalt liners.
V4-1 to V4-7	-	[None].
V5-1	-	Obtain more information (of all types) on spray-on liners, both those used on soil and those used on cement.
V5-1	-	Provide guidance on how to seal concrete (especially joints) used for TSDF impoundments.
V5-2 to V5-5	-	[None].

- Characterize membrane liner behavior under a range of hydraulic conditions (especially under high hydraulic head).

- Construct field-scale models of synthetic membrane liners and monitor over several years. Study to include measurement of actual leakage rates in addition to liner durability.

- Investigate the use of liner-compatible drain systems; look at need for specially-selected gradations of stone and use of filter fabrics.

- Perform life-cycle seam study to evaluate effect of both leachate and time on seams; especially important to include adhesive seams.

- Prepare a pre-construction questionnaire, similar to the one used for this study, for joint completion by designer and owner. Purpose would be to make them aware of key considerations in design, construction, operation and closure stages of lined site.

- Conduct experiments on seam creep.

- Evaluate techniques for connecting (sealing) liners to appurtenant structures; establish standard design methodology.

- Investigate the performance characteristics of combined FML- soil liner systems. Develop appropriate design technology.

- Standardize seam tests; evaluate each with respect to their validity for particular types of seams.

- Perform accelerated leachate-liner compatibility tests and compare results to actual "field-aged" [and field-exposed] liners. Develop predictive relationships based on the results.

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APPENDIX A

VENDOR QUESTIONNAIRE

Each vendor supplying information for this program was asked to respond to each item in the attached questionnaire using information from their own files.

The major sections of the questionnaire are as follows:

I. General Information

II. Principals Associated with the Liner Manufacture, Fabrication, Installation, Selection

III. Detailed Site Information and Design

- A. Local Geology, Hydrogeology
- B. Facility Description
- C. Site Preparation
- D. Regulatory Issues

IV. Liner Selection

V. Liner Installation

- A. Liner Layout
- B. Field Seams
- C. Other Installation Factors

VI. Lined Facility Operations and Performance

VII. Identified Problems and Corrective Action

VIII. Contained Material

IX. Comments on Successes

QUESTIONNAIRE FOR HAZARDOUS WASTE DISPOSAL FACILITIES LINED WITH PRE-FORMED SYNTHETIC MATERIAL

Completed by: ______________________ Telephone: (   ) __________
(name)

______________________ Date: __________
(company)

I. GENERAL INFORMATION

1. Name of site owner/operator (to be coded).
2. Location (city, state, country) (to be coded).
3. Principal activity at site (e.g., chemical plant, waste disposal, ...).
4. Purpose for lined facility (e.g., landfill, surface impoundment, reservoir, ...).
5. Date of installation; dates, if more than one.
6. Status of lined facility (operating/closed).
7. Climatic zone - tropical, temperate, etc.
8. Weather during installation of lined facility.
9. Climatic conditions at the facility - average temperature and extremes, humidity, precipitation, number of sun days, prevailing wind and speed, etc.

II. PRINCIPALS ASSOCIATED WITH THE LINER MANUFACTURE, FABRICATION, INSTALLATION, SELECTION

1. Please identify the companies (if known) that fulfilled the following functions:

   a) Design Engineer (or Consultant)
   b) Installer
   c) Liner Fabricator
   d) Sheeting Compounder/Fabricator
   e) Resin Manufacturer
   f) Testing of Liner (e.g., waste compatibility)
   g) Physical Testing of Liner (for strength, etc.)
   h) General Contractor
   i) Other(s) (specify role)

   [These company names will be coded.]

2. Describe the extent to which these companies interacted on this job.

3. Describe the reasons for selection of the above companies (e.g., established team, recognized for high quality work, low cost, worked with them in the past on similar or dissimilar matter, etc).

4. Other comments on principals involved.

III. DETAILED SITE INFORMATION AND DESIGN

A. Local Geology, Hydrogeology

1. Was a study conducted of the local soils and/or hydrogeology? If yes, please describe the extent of the study on an attached sheet.

2. Types of:

   a. In situ soils at site - organic, previously polluted, other (specify)
   b. Underlying rock - solubility, sensitivity to acids, other (specify)
   c. Geologic structure - existing cavities, cracks, other (specify)
   d. Cover material
   e. Vegetation - grass, trees, other (specify)

3. Permeability of in situ soils.

4. Depth to groundwater.

5. Groundwater flow rate and direction, level and fluctuation.

6. General topology of land surface - mountainous, hilly, flat, other (specify).

7. Site elevation.

8. Other details you feel are important.

B. Facility Description

1. Provide simple overall plan showing adjacent facilities, buildings, roads, rivers, orientation with respect to north, etc.

2. Geometric configuration - rectangular, square, circular, other (draw sketch).

3. Size of disposal site: surface area, depth, volume.

4. Typical cross section of site.

5. Height of liquid storage - free board height, maximum operating depth.

6. Sidewall slopes (ratio or percent) - subgrade and finished grade.

7. How and by whom was this geometry selected - were the selections of geometry and orientation affected by operational considerations, by design considerations such as wind-generated waves, topographical considerations, other (please specify)?

8. Position of bottom with respect to orginal ground surface

   a. Was there excavation of bottom?
   b. If yes, attach typical cross sections of the facility showing original ground surface.

9. Site selection - why, how, and by whom was the site selected?

10. Was a conceptual design made? If yes, by whom?

11. Provide a summary of conceptual design to include:

    a. Design criteria
    b. Type of lining system - double liner with our without intermediate drainage liner over compacted clay, liner over geotextile (give type, polymer, mass per unit area), other (specify)
    c. If drainage system, give specifications of aggregate, pipe, geotextile, and indicate location
    d. Subgrade specifications - type of material, method of compaction
    e. Earth cover specifications

12. Is the facility single- or double-lined?

13. Surface area of liner.

14. Is the liner exposed or buried?

15. Describe the layers above and below the liner(s) e.g., description of material and thickness, attach a diagram if many layers are involved.

16. Describe the extent to which drains and vents were part of the liner system. Attach a diagram if possible.

17. Is there a monitoring system under the liner? If so, what type?

18. Describe any other important or special design specifications for the site.

19. Provide other details you feel are pertinent.

C. Site Preparation

1. Describe preparation of the subgrade (e.g., compaction, chemical treatment, vegetation removed, raked subgrade, type of equipment).

2. Describe quality control and tests used to verify subgrade quality.

3. Describe preparation of sidewalls.

4. Describe quality control and tests used to verify sidewall quality.

5. Subgrade conditions at time of installation - was there excessive moisture, loose aggregate, other (specify)?

6. Were there unusual construction problems?

D. Regulatory Issues

1. What permits were obtained for the facility? and from whom?

2. Describe special requirements made by regulatory agencies (e.g., EPA, state environmental agency).

IV. LINER SELECTION

1. Identify liner material selected - brand, base polymer type - PVC, HDPE, CPE, CSPE, butyl rubber, other.

2. Thickness in mils.

3. Was the sheet material reinforced? If yes, give scrim characteristics:

   a. Count (number of yarns per unit width)
   b. Linear density (in tex or denier)
   c. Polymer (polyester or polypropylene)

4. What were the manufacturing/fabrication (if any) characteristics?

   a. Roll width
   b. Size of blankets or panels
   c. Method of factory seaming
   d. Seam width
   e. Are seams covered by a cap strip?

5. Provide physical/mechanical specification data for the liner. (Attach specification sheet)(e.g., tensile strength, elongation at break, water adsorption, etc.)

6. Was the liner pre-tested? If so, for how long and under what conditions?

7. Provide information on extent of any waste-liner compatibility tests that were conducted (attach details on type, duration of tests, and results).

8. If compatibility tests were conducted, who interpreted the data, on what basis, and provided subsequent conclusion/guarantees? (Who conducted the compatibility tests should be listed in Section II - Principals.)

9. Describe the process by which the liner was selected. (Were design or performance specifications prepared? By whom? Were competitive bids solicited? To what extent did all the bidders propose to meet the design or performance specifications? To what extent was the liner selection based on price?) Who selected the liner?

10. Describe the key elements of any guarantee or warranty associated with the liner. (Who provided it?)

11. Do you feel the best liner was selected? (Comments welcome.)

V. LINER INSTALLATION

A. Liner Layout

1. How many liner panels were used?

2. What size panels were used?

3. Describe the layout of the panels.

4. Were layout drawings available? (Attach available drawings.)

B. Field Seams

1. Describe the number and location of field seams required. Provide a seaming plan with field and factory seams; indicate location of cap strips, if any.

2. How many linear feet of field seams were used?

3. What type or style of field seam was used? (Attach diagram.)

4. Describe the procedure used for field seaming - equipment, material, technique - hot air or hot wedge seaming, adhesive seaming, other (specify).

5. What method(s) was used for inspecting and testing the field seams?

6. What percentage of the field seams were inspected?

7. How many leaks were identified/repaired (If details not available, provide a rough estimate, number identified/repaired to total number of seams, or a percentage).

8. What was the time lag between layout of the panels and field seaming?

9. What problems were encountered during field seaming?

10. Other comments on field seams?

C. Other Installation Factors

1. What was the construction schedule? What was the actual construction time?

2. Were there any unusual construction problems?

3. Were the panels inspected after layout? Describe any penetrations through the lining system - concrete structure, pipe, other (specify). Attach drawings.

4. Describe earth cover procedures

    a. Depth of cover
    b. Method of compaction
    c. Equipment used
    d. Slope compaction and/or horizontal compaction
    e. Selected material
    f. Size of largest stones
    g. Use of a geotextile beneath the cover; if any, give type, polymer, and mass per unit area

5. Were there manufacturing representatives available during installation? Were they present during installation?

6. Was the installation crew experienced?

7. Was there a quality assurance program? If yes, describe the program (visual inspection, non-destructive testing of seams, destructive testing of seams on cut-off samples, field test seams on cut-off samples) for each of the following areas:

    a. Manufacturing plant
    b. Fabrication plant
    c. Site installation
    d. Post installation - coupon monitoring program, other (specify).

8. Who provided the quality assurance program - owner, designer? Who was responsible?

9. Were there special provisions in the quality assurance program - coupon tested in laboratory?

10. Describe any other aspects of the installation that you feel were important (equipment, skill level of personnel used, weather factors, cooperation between contractors, inspection and acceptance, etc.).

VI. LINED FACILITY OPERATIONS AND PERFORMANCE

1. Describe, if possible, the "normal" operations at the lined facility (after installation).

2. Are there any aspects of the operations that may affect (or have affected) liner serviceability?

3. How long has the site been in operation? If closed, what was the operation life?

4. How long are these operations expected to continue?

5. Are there (or were there) any procedures in effect to periodically inspect and test the liner, or in any other wasy to assess its potentiual for continued serviceability? (If yes, please provide details.)

VII. IDENTIFIED PROBLEMS AND CORRECTIVE ACTION

For each identified problem, we would appreciate the following type of information: (Supply details on attached sheets, if necessary).

1. Date problem was reported or identified.

2. How was problem first identified/detected (monitoring wells, leak detection system, visual inspection, etc.)?

3. Describe the nature of the problem (i.e., what physically happened, what damage resulted, alleged cause, where it occurred).

4. Describe the significance of the problem (e.g., waste escaped, reduced service life, etc.).

5. Ascribe, if possible, the identified problem to prior "failures" (e.g., to poor design, wrong liner materials, poor installation practices, etc.).

6. What prior action(s), if taken, would have prevented the identified problems? Are these actions reasonable and part of "good engineering practice"?

7. What corrective action was taken (if any) after the problem was identified?

8. If failure occurred, was it repaired?

9. If repaired:

   a. How was it repaired - removal of substance, replacement of liner, installation of geotextile, other (specify)?
   b. When was it repaired?
   c. What difficulties, if any, were encountered?
   d. Was there a repair design? If so, by whom?

10. Has improvement in projects eventually built been observed?

11. What additional corrective action should have been taken?

12. Were any samples of the affected liner removed from the site for laboratory testing? (If yes, supply details - What, how long, under what test conditions, etc.?)

13. Was there any special investigation?

14. Is the liner still functioning?

15. Other comments on problems.

VIII. CONTAINED MATERIAL

1. Describe the type of material contained in the lined facility - liquid, solid, slurry, sludge, other (specify). Give a general description.

2. What is the chemical composition, if known, of the contained material?

   a. What are the known chemicals, their concentrations and proportions.
   b. What is the source of information - owner, independent testing laboratory, regulatory agency?
   c. What is the correlation of the material actually being handled with the design composition? What materials was the lined facility designed to handle?

3. What are the physical characteristics - shape, temperature, flow conditions, in the case of liquids such as current or flow velocity (describe agitators, causing current, if any).

IX. COMMENTS ON SUCCESSES

1. Describe key aspects of the liner (its selection, installation, use, etc.) and this facility that may be considered a success with regard to providing a long-term facility for the intended purpose.

2. If the liner is still functioning, give some possible reasons - lessons learned from previous accidents, careful design and installation, other (specify).

APPENDIX B

VENDOR SUMMARY REPORTS

Each vendor supplying case study data for this program was also required to submit a summary, letter-style report. Their reports were to provide their own opinions, based on data from the case studies as well as other projects they had knowledge of, on the factors relating to "success" and "failure" for synthetic liner installations. They were also asked to provide recommendations for future research and development that would lead to better liner systems in the future.

Each of the five vendor reports is reproduced verbatim on the following pages. The only changes made (by Arthur D. Little, Inc.) have been the substitution of appropriate codes for company names and sites, and the removal of salutations or other personal comments.

SUMMARY REPORT BY VENDOR V1

(January 16, 1984)

The following information is in response to your inquiry of the synthetic membrane liner assessment project and is to be accepted as Task III, the analysis of data, and Task IV, areas for research.

Analysis of Data

The following points can be made upon analysis of the data previously submitted which would lead to a successful installation of a flexible membrane liner system for liquid containment and pollution control:

1. Proper Design Engineering As the initial step, it is the most critical. A total assessment of the project must be made, including the wastes to be contained, the site selection, and subsurface strata involved. From this information, the potential solutions can then be analyzed.

2. Proper Material Selection A critical factor is that the material selected must not only be compatible with the effluent to be contained. Other factors to be concerned with include longevity of the material, resistance to ultraviolet degradation if applicable, resistance to microbacterial attack, the seamability of the material, elongation, temperature extremes, puncture resistance, conditions anticipated during installation, groundwater, seismic action, and subsurface conditions. Failures can occur if the above mentioned items are not addressed.

3. Proper Earthwork Preparation As a flexible membrane liner system in itself is not a load bearing system, it is imperative that the subsurface preparation be of sufficient quality to effect long service life. This includes proper compaction of the bottom and sideslopes to in most instances a minimum of 95% proctor. The surface preparation should be smooth and free of objects which could puncture the lining system. If groundwater is present methods should be instituted to correct the problem. If gases are present methods need to be utilized to vent them off. As the final step before installation of the lining system, the owner, engineer, and installation contractor should approve and verify that the earthwork preparation is satisfactory.

4. Proper Lining Installation As the last step a lining system installation it should be realized that even the best lining system, properly engineered and designed, with proper earthwork preparation, and utilizing the best lining system available will be unsatisfactory and lead to a failure if the material is not properly installed. Poor workmanship and quality control is a major cause of liner failures and

is a justification for utilization of an experienced lining installation contractor. As no two installations are similar, it is important to have experienced personnel to adjust to the nuances and conditions of each particular installation and to insure the lining system integrity is maintained. In most cases the total lining project will proceed more smoother and quicker and any problems which might occur can be either precluded or handled more efficiently and effectively. A specification requirement of a minimum amount of installation experience should be incorporated.

5. Proper Maintenance of the Lining System As minor unintentional damage does occasionally occur, it is a good practice to have operating personnel be familiar with maintenance procedures for attending to minor damage to the lining system. In many cases where minor damage has occurred and not been corrected, major problems have developed to the stage where major repairs and replacements have been necessary. The materials and procedures for affecting repairs should also be taken into consideration during the material selection process as in all cases minor repairs and maintenance will be required.

Areas for Research

As it is our feeling that the industry in itself has done a relatively poor job in policing itself, we would highly recommend that research be directed to determining consistent quality standards for membrane liner materials. These tests and subsequent standards would enable objective comparisons of materials. Presently, current testing methods and standards are not totally applicable in determining the serviceability, applicability, and longevity of membrane liners in service applications. In many cases engineers and owners look only at physical specifications for liner materials without regard to the application and serviceability. As of this writing, there are no definitive standards present in the market place which would enable someone without considerable experience in flexible membrane liner systems to determine the best material for individual applications. With the present popularity and need for quality membrane lining systems, it can be observed where many new materials are being marketed and installed without proper qualifications for application which can only lead to more problems in the future.

SUMMARY REPORT BY VENDOR V2

(December 22, 1983)

Case History V2-1: Conclusions and Recommendations

This large, multi-cell, lined pond installation in the Southeastern part of the United States has been successfully operating for over ten (10) years. Part of the success of this installation is due to the extensive pre-testing of the liner material and its ability to handle the effluent present, as well as to properly vent anticipated gas generation. The careful analysis of the different materials suitable for the job, along with their seamability and the effectiveness of their adhesive systems also contributed to the success of this installation.

An unexpected chemical attack problem occurred when a defoamer, used in extremely small quantities, was changed from water base to oil base. Although present in the effluent in only parts per million, this oil based defoamer floated to the surface and plated out at the liquid level around the perimeter of the ponds. Over a period of time, this provided a very concentrated attack on the Hypalon lining material at the liquid level of the ponds.

Once the problem was identified, a switch back to a water based defoamer prevented further damage from occurring, and in fact allowed the membrane liner to recover to a large degree from the damage previously inflected.

The repair program to cover severe damage at the liquid level around the perimeter of the ponds has shown that the lining material can be successfully cleaned and seamed even after six to seven years to field exposure.

Our recommendations, based on the experience of this Case History, are as follows:

1. Even if a chemical compatibility test is run prior to the selection of a membrane, careful controls on the constituents in the effluent must be maintained to prevent possible unforeseen damage.

2. A concentrated attack at the liquid level of an accumulation of trace chemicals can cause serious problems over a long period of time. Most chemical immersion studies will not reflect this potential for damage, as the sample is small and any harmful chemicals are quickly exhausted into the liner, thus preventing further damage.

3. Routine maintenance and inspection of the flexible membrane lining material is essential to detect damage in its early stages, so that corrective action can be taken before a major disaster occurs.

4. Use of multiple cells allows one or more of the cells to be taken out of service for inspection and repair without shutting down the entire system. It is always desirable to construct large installations with multiple cells. This not only allows one or more cells to be taken out of service without shutting down the facility, but also facilitates the location of any damage and minimizes the adverse affects on the environment.

Case History V2-2 Conclusions and Recommendations:

This 1971 installation in the north Midwest was made before the full effects of gas generation under a membrane liner were clearly understood. Once the gas collection had started under the liner, it was not possible to correct the basic error in the slope of the pond bottom that was responsible for the failure.

This is a classic example of the need to properly design a flexible membrane lining installation prior to installation and use. Basic errors in the earth work, resulting in a flat pond bottom that would not vent collective gases, could not be overcome by emergency repair methods.

Our recommendations, based on the experience from the Case History, are as follows:

1. All liquid container ponds should have a sloped bottom. The slope should be a minimum of 1-½ to 2% from the lowest point up toward the sloping berms of the pond to enable generated gas to move out and up the slopes for venting.

2. Reuse of an unlined or clay-lined pond where organic materials have been stored should be treated as a gas generating potential problems.

3. It is virtually impossible to correct a gas generating bubble problem without completely re-excavating and re-sloping the earth work.

4. Gas vents around the perimeter of a pond are only effective if the bottom and slopes direct the gas toward the vent system.

5. Cutting the liner to relieve gas pressure only compounds the problem, as it releases more organic fluids into the soil with resultant increased gas generation.

Case History V2-3: Conclusions and Recommendations:

This Case History analyzed a successful waste liquid impoundment in Northern California. Unsupported Hypalon membrane was installed in the initial pond in 1971, and has performed very well since that time.

Factors contributing to this successful installation are as follows:

1. The effluent had been clearly identified, and performance in similar effluents had been well documented prior to the installation.

2. Unsupported Hypalon was used over a compacted sand base. The unsupported material gave maximum ability for the membrane liner to adjust to minor settling experienced.

3. The only significant damage to the membrane liner was due to mechanical damage from a tank truck that slipped down one bank of the pond, damaging the lining material. However, due to the thermoplastic nature of the Hypalon, it was possible to clean up the surface, removing any surface cure and affect film tearing bonds using Hypalon-to Hypalon adhesive even after a number of years of exposure.

4. Excellent outdoor weathering of lining material in an industrial environment has enabled the liner to continue performing over a 12 year period.

Our recommendations derived from this Case History include careful analysis of the effluent anticipated, and testing of the membrane in this or similar effluents is extremely important. The use of unsupported material with its ability to elongate and conform to settling, can be an important factor in long-term successful performance. With slopes of 3:1 or less, an unsupported membrane can provide excellent performance, in spite of lower tensile and tear properties.

The chemical, physical, and geographical requirements of each installation should be carefully considered, and a flexible membrane lining material selected to provide the optimum performance under the conditions expected.

Case History V2-4: Conclusions and Recommendations:

This successful installation of a series of landfill cells, beginning in 1974, is an excellent example of good engineering, material analysis, planning and management of the landfill operation for hazardous wastes.

Close cooperation between the resin supplier, who was also the customer, the manufacturer, fabricator and installer of the landfill liner, all contributed to the success of this operation.

The careful selection of the complete team by a sophisticated owner/user provided the utmost in reliability, without the "cost squeeze" produced by awarding the contract to the lowest bidder, regardless of experience and qualifications.

The conclusions to be derived from this case history are as follows:

1. All installations of flexible membrane liners for the containment of hazardous waste, either as landfill or liquid containment, should be based on a comprehensive analysis of all of the participants.

2. A continuity of responsibility starting with the resin manufacturer, and including the manufacturer, fabricator, installation contract, and maintenance function should be carefully coordinated. Usually the manufacturer of the flexible membrane lining material will assume the overall responsibility for performance, providing that approved, experienced and certified contractors approved by the manufacturer are used throughout the installation process.

SUMMARY REPORT BY VENDOR V3

(January 1984)

I. Introduction

Preceding this report was the survey of five sites entitled "Assessment of Synthetic Membranes for Waste Disposal Facilities to the Land" ([Vendor V3], 1983). That survey provides a detailed summary of the waste and membrane characteristics at five waste disposal sites. Conclusions can be derived from that survey regarding critical factors affecting the success and failure of synthetic membrane operations at specific installations. More generalized conclusions can be formulated using the overall experience of our scientists and engineers who are involved on a daily basis in all phases of liner design, testing and construction supervision. The following section draws on that experience, in addition to the site survey in describing those factors most critical to the overall project success at a synthetic membrane installation. These critical factors provide a framework for the recommendations presented in Section III relating to improvements in membrane system design, installation and related tasks.

II. Success and Failure Factors

The basic criteria upon which the success of any particular design is evaluated relates to its primary function. For this analysis, it is assumed that the primary motive for inclusion of a liner system to a land disposal facility design is the retardation, or prevention, of waste water (leachate) movement into surrounding groundwater systems. Secondary functions of the liner may include: Chemical modification of the leachate, traffic and equipment support, among others. Although a membrane may be able to successfully perform all secondary functions, it is likely to be considered a failure if the primary function can not be performed.

We have identified the following factors as important contributors to the failure of synthetic membrane liners:

1. Inadequate pre-selection testing of the liner. Often the liner is laboratory tested under conditions which are vastly different from the in-place environment. Specifically, leakage tests are often conducted at hydraulic gradients which are less than that expected in the field. Also, pre-selection testing is based on manufacturers' tests which may be biased towards their materials. Manufacturers' tests are quality control oriented and do not relate specifically to performance.

2. Inadequate quality assurance programs were established. The quality assurance program should include well defined standards of visual, destructive and non-destructive tests. None of the five sites included in the Assessment Survey had a quality assurance program of this sort.

3. Inadequate leachate control systems above the membrane liner. We have seen that failure of the leachate control systems (i.e. gravity drainage piping or pumped systems) often precedes the actual failure of the liner. The control system is designed to accommodate X gpm of leachate at a specified head. However, when the actual leachate generation rate exceeds X, excessive hydraulic heads may develop and induce seepage through and/or tearing of the liner (i.e., hydraulic or structural failure). This is especially possible in combination with factor 4, below.

4. Liner contact with poorly selected and placed gravel drains. Puncture of the membrane occurs when the interfacing drain layers are either too heavy for the membrane, placed haphazardly or are characterized by excessively sharp edges. Although the resulting punctures are small enough that they may not impact the liner significantly during normal operating conditions, problems develop as factor 2, above, comes into play.

5. Use of heavy construction equipment. Several cases have been reported which suggest that use of heavy equipment before adequate support is developed into the liner system is a major failure factor. Often this occurs if the liner construction proceeds at variable rates at a single site. Without adequate direction, the contractor may haul his equipment over a less-complete portion of the landfill unknowingly.

6. Leakage around vertical risers. Manhole risers from underdrain systems and monitoring wells protrude through the liner. This can lead to problems because of the inability to obtain an effective bond between the membrane and riser. As seepage between the two occurs, the separation distance increases and a major failure path is formed.

7. Ineffective membrane seams. Whenever the largest dimension of the covered area exceeds the "as-manufactured" width of the membrane panels, seaming is required. This may occur in the field or factory. Although factory seaming is superior, most often field seaming is used because of transportation and construction problems associated with large, pre-seamed panels. Field seams are susceptible to problems associated with poor weather conditions, inadequate supervision, inexperienced seamers, etc.

The factors leading to success are intimately related to the failure factors mentioned above. Successful installations have been able to limit, or eliminate, the six failure factors identified previously. In general the successful installations are those with the least complex design and those having an "as-built" condition most similar to the design plans. Although poorly designed or constructed sites are often not labeled failures, this is likely more attributable to inadequate or absent monitoring systems at these sites.

III. Research Recommendations

1. Initiate a study, similar to the present one, which considers only the variation of seaming techniques. Each of the synthetic membrane installations investigated as a part of this study had some problem with seam construction or operation. This is obviously a key problem, but has not been studied in sufficient detail under the broad concerns of the present study. As a product of the proposed study, a design matrix could be developed indicating the compatibility between the different seaming techniques and membrane materials, application environments, waste characteristics, budget requirements, etc.

2. Develop improved methodologies for estimating the rate of leachate movement through the waste disposal facility. The leachate volume expected to contact the liner on a monthly or daily basis should be a major consideration in the design of the bottom liner. In addition, the total volume of leachate and maximum rate of leachate movement to the liner should be considered during the design. However, the current methodology for these predictions is severely lacking. The two most widely referenced methods, the Water Balance Method, EPA/530/SW-168/, and the HSSWDS (Hydrologic Simulation on Solid Waste Disposal Sites) Model, EPA-SW-868, should be considered unverified and extremely approximate. Until accurate predictions of the leachate generation rate are available, overly conservative designs will be required to prevent flooding of the leachate control system and waste migration through the liner.

3. Characterize the membrane liner behavior under a range of hydraulic conditions. Currently, laboratory tests are often performed at a specific head, (for example, the equivalent of one foot of water), if at all. However, actual operating conditions may vary significantly, especially in the case of failure of the leachate control system.

This investigation would allow the development of a head-discharge relationship for the membrane, valid over a broad range of operation. The information could be used (in combination with 2, above) in a computer model to simulate the dynamic, rather than static, transport processes through the liner. Ultimately, improved predictions of migration through the membrane in field conditions would result. This would be used in both the landfill design and analysis phase.

4. Construct field scale models of synthetic membrane liners and monitor over several years. Although the EPA has sponsored several field scale landfill models, these have emphasized the chemical composition of leachate rather than the volumetric leakage through liners. As such, little effort has been expended to use these models as a predictive tool for leakage through synthetic membranes.

5. Investigate the use of liner compatible drain systems. Heavy stones and sharp-edged gravel in the drain systems at two of the survey sites punctured the liner. The investigations proposed here would evaluate the use of filter fabrics and specially selected gradations of stone and gravel as non-puncturing drains and filters.

6. Perform a life-cycle seam study to evaluate the effect on seams of both leachate and time. This would be an especially important study for the bonding quality of adhesive seams which are known to be time dependent. Studies of this type have been performed on liners, but not on seams.

7. The five site surveys identified seams as the weakest link in the synthetic liner containment system. Research into possible alternative seaming techniques for especially critical applications (i.e., hazardous waste disposal sites) should be initiated. Possible techniques for investigation include double seaming, overlapping seams and double liner seams.

8. A pre-construction questionnaire, similar to the one used in this survey, should be developed for circulation to liner designers. Joint completion of the questionnaire by the designer and owner would be mandatory to obtaining a construction permit from regulatory agencies. The questionnaire would serve the purpose of making the designer and owner aware of design, construction, operation and closure considerations.

9. Experimentally investigate the problem of seam creep.

10. Evaluate appropriate connection techniques between liners and appurtenant structures and establish a standardized design methodology.

11. Investigate the performance characteristics of combination synthetic membrane/soil liner systems. Develop the appropriate design technology.

12. Standardize seam tests for liner applications. The tests should be evaluated with respect to their validity for particular types of seams.

13. Perform an accelerated leachate study and compare results to actual "field-aged" liners. Based on the comparisons, develop a predictive relationship between the inner properties from the accelerated study and in-situ liner operations.

In the accelerated study, large quantities of leachate would be forced through the liner and seams to simulate the volume of an extended field life, fifty years for example. The study would evaluate the effluent quality to assess the liners long-term pollutant attenuation characteristics. We have performed similar studies for bentonite and asphaltic liners and slurry walls.

SUMMARY REPORT BY VENDOR V4

(March 12, 1984)

The following is the final analysis of the seven subject projects which we submitted. The projects picked were based on a variety of applications, length of time in service, and service conditions.

[Site V4-1]

This project is located in an area of extreme cold temperature and sandy soil conditions. The project was initially lined with 36 mil reinforced Hypalon. When we arrived at the site, Hypalon seams had separated and large areas of the Hypalon liner had delaminated. The project was subjected to extreme cold temperatures (-40°F) routinely and heavy ice loadings.

We believe that the cause of the problems were different contraction rates between the scrim and Hypalon material, and the inability of the Hypalon to resist the impact of ice loads. In addition, the slopes were non-compactable sand which would have contributed to stressing the liner.

The solution to the problem was the installation of 100 mil HDPE liner. The material is not laminated and consequently cannot experience the delamination problems of a multi-ply Hypalon. The material has extremely high puncture resistance, two times that of any other synthetic liner material, and did not puncture under the heavy ice loading. HDPE has a greater ability to elongate and thus compensate for non-compacted soil conditions.

Clearly, the design problems which had to be considered in this project were extremely cold temperatures, the consequent ice problems, and poor soil conditions on the side slopes.

[Site V4-2]

This project is located in a subtropical area with clay and sand soil conditions. The impoundment is used for storing brine water from a deep well fuel storage facility. This project was initially lined with 36 mil reinforced EPDM. The project was in service for approximately 6 years. Most of the failures of the liner were in the seam area.

We believe the brine liquid had a small amount of alphatic hydrocarbons, aromatic hydrocarbons, and crude petroleum products which concentrated at the liquid surface causing the liner to fail. It appeared that the seam area failed due to the incompatible chemical attack. This would allow liquids to escape to the soil and create a deteriorated subgrade condition. The deteriorated subgrade condition would then cause additional stresses on the EPDM liner and propagate the initial failure.

The solution was the installation of a 100 mil HDPE liner. The thickness allowed for differential settlement without jeopardizing the integrity of the liner. The HDPE material was compatible with the chemical loading (hydrocarbons) and consequently would last the anticipated service life.

The problems associated with this project were chemical resistance and elongation of the material.

[Site V4-3]

This project is located in an arid area. The soil conditions were rocky with well graded sands. The only liner material installed at this site was HDPE. Water in the area is an expensive commodity. It is critical to the area that contaminated water from the power plant not pollute the aquifers below.

Based on careful evaluation of liner materials and installation systems as related to the types of containment expected and required service life, HDPE manufactured and installed by [V4] was chosen. The thickness ranges from 60 mil to 100 mil depending on service requirements. The owner chose to up-grade their liner thickness in order to gain the system security required.

[Site V4-4]

This project is located in the Continental zone and is a Class 1 hazardous waste site. The soils are sand and clay layers. Cell #4 of this project used clay only as a liner. Cell #5 used clay and a Hypalon liner. Cells #6 and #7 are lined with a clay and HDPE. We believe this project has followed the evaluation of the lining market over the past few years. Clay was thought to be an acceptable liner until it was discovered that chemical waste would cause clay to become porous and crack. Hypalon is known to be a liner material with limited chemical resistance. Currently, HDPE as a liner material has the widest range of chemical resistivity and highest puncture resistance. These properties combined with good elongation, high tensile strength, and good UV resistance provide good liner service life in an industry which now demands better liner performance.

The design problem associated with this site is a wide range of chemicals in contact with the liner and an unknown end resultant chemical at times. It should be noted that Cell #6 was a 60 mil HDPE liner and Cell #7 was an 80 mil HDPE liner. The reason the client went to a thicker material was the operation problems with the 60 mil HDPE and a need to increase the puncture resistance.

[Site V4-5]

This project lies in the Continental zone. The soils were clays in the area [V4] was to work in. The original liner was a 10 foot

clay embankment. The holding basins were built over the existing landfill area. This area was experiencing differential settlement and the clay liner cracked. Consequently, the leachate being held for treatment started leaking.

The solution to the problem was the installation of an 80 mil HDPE liner. The material (HDPE) would be able to take the wide range of unknown chemicals encountered from the combined industrial and municipal waste site. The 80 mil thickness was chosen because of the expected differential settlement. HDPE has high elongation properties which would allow for differential settlement. The material would be able to bridge the cracks in the clay and not allow leaks to develop.

[Site V4-6]

The project lies in the Temperate zone. The soil the liner was applied to was sandy. The major problem with this project was the chemicals to be contained. Initially, a Hypalon liner was installed. It is our understanding from the client that this liner failed due to chemical incompatibility in a short period of time.

The solution to the problem was the installation of a 100 mil HDPE liner. The HDPE had the chemical resistance required and offered a long term solution.

[Site V4-7]

This project is located in a semi-arid region with clay and sandy soil. The only liner material installed at this site is HDPE. Water in the area is an expensive commodity. It is critical to the area that contaminated water not reach the aquifers below. Irrigation is widespread in the region for farming.

Based on careful evaluation of liner materials and installation systems as they relate to the type of pollutants expected and required service life, HDPE manufactured and installed by [V4] was chosen. The thickness utilized for this project was 80 mil HDPE.

Summary

In reviewing all of the above projects, it has become apparent that liners fail for different reasons. The principal reasons are chemical incompatibility, low mechanical strength resulting in poor tear and puncture resistance, and poor seaming. Soil conditions such as compactibility and stability play an important role in liner integrity. In all cases, testing between the failed liner material and waste to be contained was not performed prior to construction.

We would make the following recommendations when selecting a liner system:

1. Liner Material - Compatibility testing should be performed between the liner material and waste to be contained. In those cases where the waste stream is unknown, the liner material with the widest range of chemical resistance should be chosen.

2. Puncture Resistance - This design parameter is often underestimated. Loads due to construction of the liner system such as placement of a soil cover, operation of the facility such as ice and/or wave action, and maintenance of the facility such as mechanical clean-out or hydraulic cleaning can apply point stress loads. There are many unknowns and changed parameters made in this area. From past history it is evident that in general thin liners have not demonstrated adequate puncture resistance and must be upgraded.

3. Seaming - Some seaming methods utilized different materials than the base. These must be checked as they relate to chemical compatibility. This is the area the human element is introduced during construction. We recommend a requirement of at least 100% bond strength of a seam. This allows all the other values listed for a material to be equal to its seam strength. The key to seaming is a tough Quality Control program. We recommend both destructive and non-destructive testing in the field during construction. We also recommend that the non-destructive test be on 100% of the weld seams and the destructive testing be checked by an off-site laboratory.

SUMMARY REPORT BY VENDOR V5

(March 3, 1984)

1. Overall conclusions of success and failure factors:

The five representative ponds which were submitted to your office can be considered representative and typical of the seven hundred plastic lining jobs completed by [Company UU]. When considering all of [Company UU] plastic lining jobs the predominate purposes are water pollution control and water conservation. Pollution control predominates in dollar magnitude of business performed since 1969. Prior to 1969 the principal lining materials used clay (Bentonite), PVC and Polyethylene plastic sheets.

Agriculturalists soon began to recognize the value of imploying conservation practices in their irrigation reservoirs. The importance of conservation becoming more noticeable as the ground water was increasingly being tapped as the primary source of water for the irrigation water supply. The attendant pumping power bills became a monthly reminder to the individual farmers.

The use of plastic membranes after WWII became a viable economic alternate to the natural clays.

The ponds installed by the company have demonstrated a very high success ratio of performance. This statement is made considering all the reservoirs, lakes and ponds installed and also considering all of the types of natural and plastic membranes which have been installed.

Plastic as well as natural membranes installed by [Company UU] have on occasion failed in the purpose intended. The failure in almost all cases was mechanical in nature although there was one notorious chemical failure. The mechanical failures are caused by punctures, flooding (washouts) and erosion of the side slope cover material which allows ultraviolet attack. The puncture failures, occurring after completion of the lining, result from grazing stock, rodents, pole penetration when persons are boating or rafting, or by persons making repair or additions to pipelines under the membrane, or repairs to inlet and outlet structures. Puncture failures occurring before the pond is put into service normally are caught; however, this has been shown to be not always the case.

Reservoir water level management has, on several occasions, been the cause of membrane ruptures.

Ultraviolet attack has caused at least twenty to thirty failures in the ponds constructed by the company. These occurred because of design failure, side slopes to steep, and lack of maintenance (not keeping dirt cover over the membrane on the side slopes). The clients were warned of this inevitability prior to beginning lining installation.

There was one chemical failure of which this company was aware. The material was a 30 mil RCPE. The climate at the site was coastal with a relatively high humidity. The design required the top liner to be left uncovered. This liner was inhibited from ultraviolet attack. Just prior to putting the liner into service, which was two months after contract completion, the owners engineer made a routine inspection. He observed several field seam separations. His comment "he could separate the lap joint like removing a wet postage stamp". The field seams were redone three additional times, each time under careful supervision of chemists and engineers of the resin manufacturer. Six months following the third reseaming, the CPE film between the reinforcing threads vaporized leaving particles attached to the threads.

Shortly thereafter the sheeting manufacturers, who also compounded the mix, admitted they had made a mistake when they compounded the CPE. It was admitted that PVC resins had been combined with CPE resins and the combination in the end product had very high hydroscopic properties. Our tests showed up to 46% water absorption had occurred. The pond was redone using chlorosulfonated polyethylene (Hypalon).

2. Recommendations:

(a). In selecting membranes for a pond, do not place PVC in close proximity (touching) to a CPE membrane.

The plasticizer used in compounding PVC will migrate to the CPE. This will result in a brittle PVC liner and a very soft CPE liner at the contact area.

(b). Membrane system design is a function of the allowable concentration of pollutants over an arbitrarily designated period of time.

If the conclusive criteria is set at zero pollution, then more than two impervious liners may be required. The liners above the lower two must be on a platform which will allow for their relatively easy replacement. My personal assessment of the pollution control programs would indicate that EPA policy decisions must be tempered by the economic factors facing our industrial, mining and manufacturing and agribusiness complexes who are competing with all countries on the world market. Competitive strangulation of our industrial sectors is self liquidating to the United States population.

APPENDIX C

SUMMARY DATA

This Appendix presents a one-page data summary for each of the 27 facilities analyzed in this report. The summary includes basic information on facility operation and liner characteristics, including a generalized schematic diagram of the liner system. The first page of the Appendix is a key describing the information given on each line of the summary sheet. Question marks are used to indicate entries which are unclear based on data provided by the vendors. Comments given on the last line of the summary sheet and in the Problems section reflect the Vendor's assessment of system performance and are independent of the analyses presented in the body of the report.

SITE: Identifier

LOCATION: Place

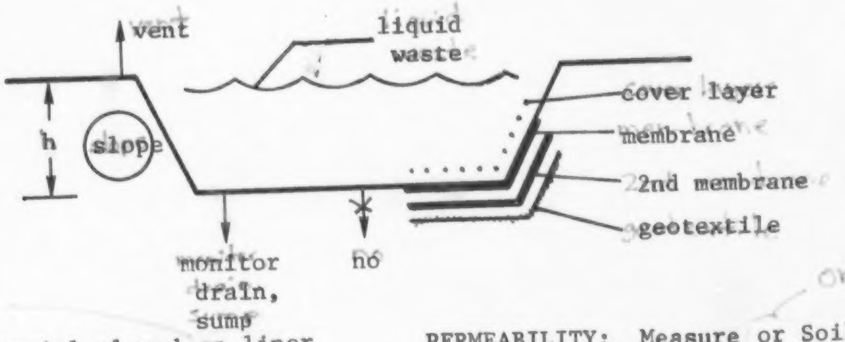
PURPOSE: Operational Type of Site

WASTE: Type; Composition

YEARS OPERATIONAL: Years

PROJECTED OPERATION: Years or Period

FACILITY: Shape; area


vent
liquid waste
cover layer
h
slope
membrane
2nd membrane
geotextile
monitor drain, sump
no

COVER: Material placed on liner

PERMEABILITY: Measure or Soil Type

BASE: Material under liner

GROUNDWATER: Level under membrane or site

SUBSOIL: Material under base

LAND: Basic topography and area description

LINER MATERIAL: Type; thickness; reinforcement; number

COMPATIBILITY: Type of test on liner material

SEAMS: Factory type; linear feet in field, type of joint, test type

NUMBER OF PARTICIPANTS: Contractors all types (regulatory bodies)

PROBLEMS: General description

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS		
SITE	Describe or comment	
LINER	on problems or lack	
APPURTENANCES		
CONSTRUCTION		

COMMENTS: installation operation to date

7.

SITE: V1-1 LOCATION: Southern U.S.

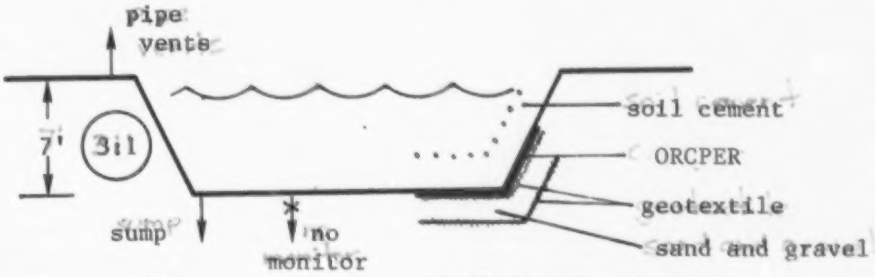
PURPOSE: Brine storage (petroleum) reservoir

WASTE: Brine (no data) w. trace hydrocarbons

YEARS OPERATIONAL: three years

PROJECTED OPERATION: operating; indefinite

FACILITY: Two rectangular cells; 10 acres total



ORCPER

ORCPER

COVER: Soil cement (8") PERMEABILITY: Unknown

BASE: sand and gravel (6") GROUNDWATER: Near or at groundwater

SUBSOIL: compacted; unknown LAND: previous marsh, flat

LINER MATERIAL: ORCPER; 36 mil; reinforced

ORCPER

COMPATIBILITY: Tests unknown - Manufacturer's recommendation

SEAMS: Dielectric factory; 5,500 LF field; filled adhesive; 100% test

NUMBER OF PARTICIPANTS: 6(?)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems reported No data provided
SITE	2nd pond lining system for this marsh area	
LINER	No problems	
APPURTENANCES	No problems	
CONSTRUCTION	Finished ahead of schedule; some problem placing liner over geotextile fabric	

COMMENTS: Successful installation Operational without problems after 3 years

SITE: V1-2 LOCATION: Southern USA

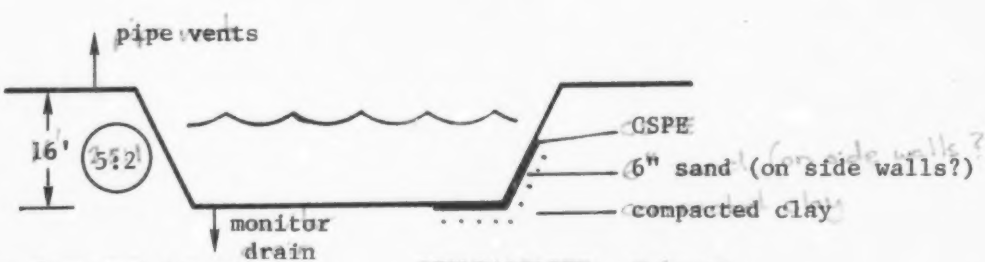
PURPOSE: Brine storage (petroleum) reservoir

WASTE: Brine (no data)

YEARS OPERATIONAL: 1 year

PROJECTED OPERATION: operating; indefinite

FACILITY: Rectangular; 22 acres (2,000,000 bbls)



COVER: None (exposed liner) PERMEABILITY: Unknown

BASE: Sand GROUNDWATER: 16'

SUBSOIL: Compacted clay LAND: Raw land, flat, clayey

LINER MATERIAL: CSPE; 36 mils; reinforced; single

COMPATIBILITY: Unknown

SEAMS: Dielectric factory; 26,000 LF field; filled adhesive; 100% test

NUMBER OF PARTICIPANTS: 6 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	Operator carelessness
SITE	Cut & fill (none)	No problems
LINER	None (no repairs)	5 holes in liner by operator
APPURTENANCES	No problems	No problems
CONSTRUCTION	Finished ahead of schedule; ground water at low end	No problems
COMMENTS:	Successful installation	Monitor detected leak, liner patched, successful operation after 1 year

SITE: V1-3 LOCATION: Southeastern U.S.

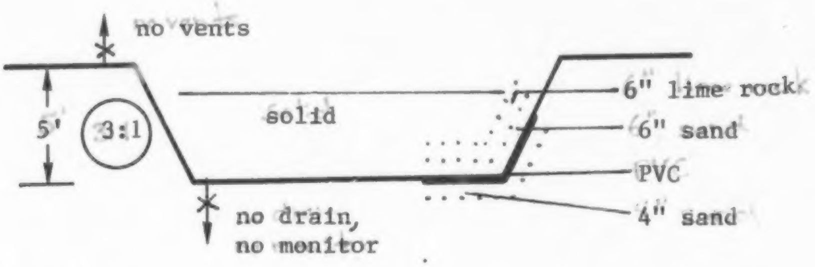
PURPOSE: Landfill

WASTE: Solid waste from incineration

YEARS OPERATIONAL: 3 years

PROJECTED OPERATION: Operating; indefinite

FACILITY: Two rectangular cells, 2 acres total



COVER: Sand and rock

PERMEABILITY: extremely permeable but unknown

BASE: Sand

GROUNDWATER: ?

SUBSOIL: Rock and sand

LAND: Flat; cleared

LINER MATERIAL: PVC; 30 mil; unreinforced; single

COMPATIBILITY: Unknown

SEAMS: Solvent factory; 2250 LF field, solvent weld; 100% test

NUMBER OF PARTICIPANTS: 5 (?)

PROBLEMS: No incipient failure

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	↕ no problems reported
SITE	none, uncompacted soil	
LINER	none, seam boards required	
APPURTENANCES	pipe penetrations required boots	
CONSTRUCTION	finished ahead of schedule	

COMMENTS: Successful installation

Operational w/o problems after 3 yrs

SITE: V1-4 LOCATION: Eastern U.S.

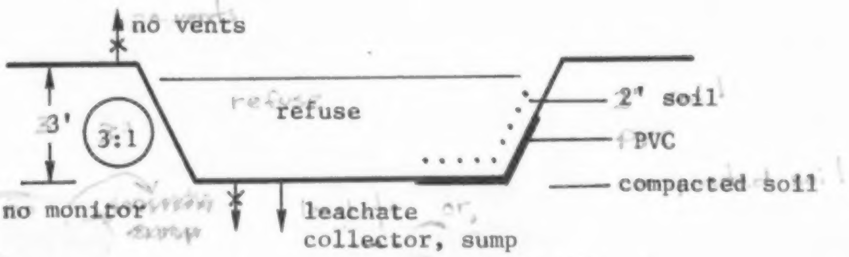
PURPOSE: Solid waste landfill

WASTE: Solid waste

YEARS OPERATIONAL: 3 years

PROJECTED OPERATION: Operational; indefinite

FACILITY: irregular area; 10 acres



COVER: Selected native soil PERMEABILITY: ?

BASE: Compacted clean soil GROUNDWATER: ?

SUBSOIL: Typical (?) LAND: Cleared; flat

LINER MATERIAL: PVC; 30 mil; unreinforced; single

COMPATIBILITY: Unknown

SEAMS: Solvent factory; 6,200 LF field; solvent weld; 100% test

NUMBER OF PARTICIPANTS: 5(?)

PROBLEMS:

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	Blowing sand during seaming	
APPURTENANCES	No problems	
CONSTRUCTION	None; finished ahead of schedule	
COMMENTS:	Successful installation	Operational w/o problems after 3 yrs

SITE: V1-5 LOCATION: Southern U.S.

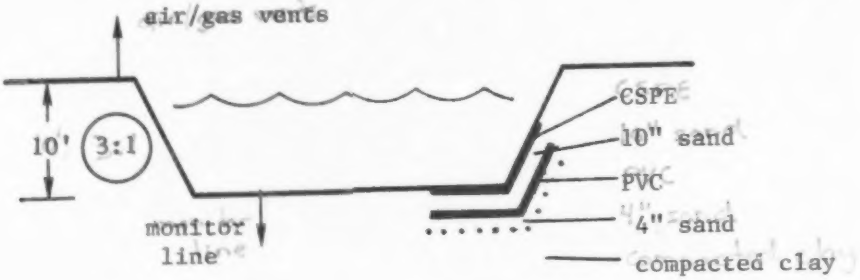
PURPOSE: Chemical Waste Holding Reservoir

WASTE: Liquid chemical wastes; composition unknown

YEARS OPERATIONAL: 3 yrs.

PROJECTED OPERATION: Operating; indefinite

FACILITY: Rectangular; 2 ponds; 1 acre total



COVER: Exposed CSPE

BASE: Sand

SUBSOIL: Clayey

PERMEABILITY: Unknown

GROUNDWATER: Unknown

LAND: Flat, reservoirs prior prepared

LINER MATERIAL: PVC, 20 mil, unreinforced
CSPE, no information, 30 mil.

COMPATIBILITY: Unknown

SEAMS: PVC, solvent factory; 50 LF field, solvent; 100% test
CSPE ? ; 750 LF field, CSPE filled adhesive; ?

NUMBER OF PARTICIPANTS: 7 (?)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	↑
SITE	Prepared prior	
LINER	No problems	No problems
APPURTENANCES	No problems	
CONSTRUCTION	Finished ahead of schedule	↓
COMMENTS:	Successful installation	Operating successfully after 3 yrs.

SITE: V1-6

LOCATION: East Central US

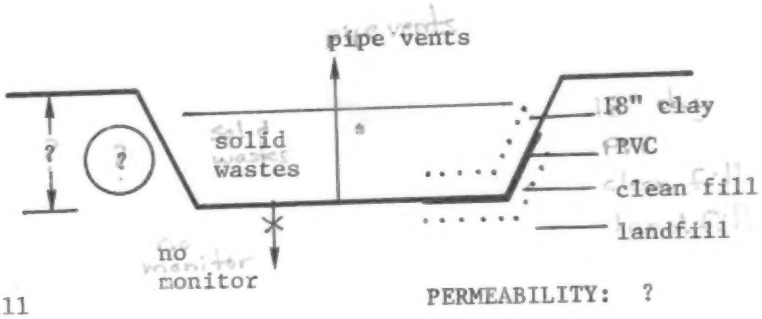
PURPOSE: Solid waste landfill (chemical plant)

WASTE: Unidentified solid chemical waste

YEARS OPERATIONAL: June 1981 installed (?)

PROJECTED OPERATION: Secured and abandoned

FACILITY: Irregular area; 2 acres



COVER: fill

PERMEABILITY: ?

BASE: clay

GROUNDWATER: ?

SUBSOIL: Previously polluted waste landfill

LAND: Hilly, near river, old waste site

LINER MATERIAL: PVC; 30 mil; unreinforced, single

COMPATIBILITY: Unknown

SEAMS: Dielectric factory; 1,000 LF field, solvent weld; 100% test

NUMBER OF PARTICIPANTS: 5 (?)

PROBLEMS:

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	No problems	
APPURTENANCES	Vert. pipes required booting	
CONSTRUCTION	Finished ahead of schedule	

COMMENTS: Successful installation

Operated successfully and presumed holding after 3 years (?)

SITE: V2-1

LOCATION: Southern U.S.

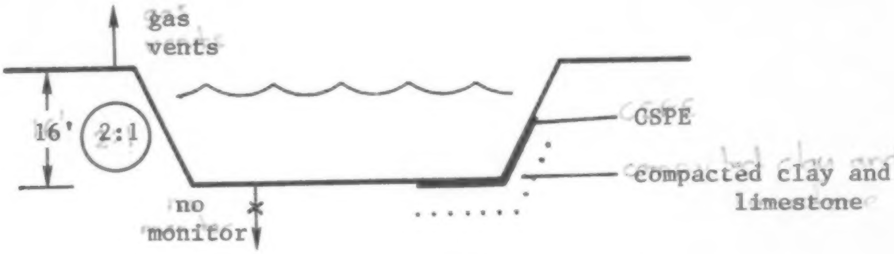
PURPOSE: Impoundment for aeration treatment

WASTE: Paper mill liquid with defoamer; clear

YEARS OPERATIONAL: 11 years

PROJECTED OPERATION: 20 years; operating

FACILITY: Shape?; 120 acres



COVER: None (exposed)

PERMEABILITY: ?

BASE: Previously failed bentonite liner and limestone

GROUNDWATER: ?

SUBSOIL: Fissured limestone

LAND: Flat; scrub pine grove area

LINER MATERIAL: CSPE; 30 mil; reinforced 8x8 nylon scrim; single

COMPATIBILITY: Yes (?)

SEAMS: Bodied adhesive factory; 25 miles Field; bodied adhesive; 100% test

NUMBER OF PARTICIPANTS: 4 (?)

PROBLEMS: Potential for gas generation due to reaction between limestone & effluent was a design problem

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problem	No problem
LINER	Some weak seams; poor cure; suspect field seams capped	Damage at liquid level (oily defoamer - not in compatibility test)
APPURTENANCES	?	?
CONSTRUCTION	Longer than schedule to complete	?
COMMENTS:	Difficulties in construction	Compatibility failure due to untested material

SITE: V2-2

LOCATION: Mid-Western U.S.

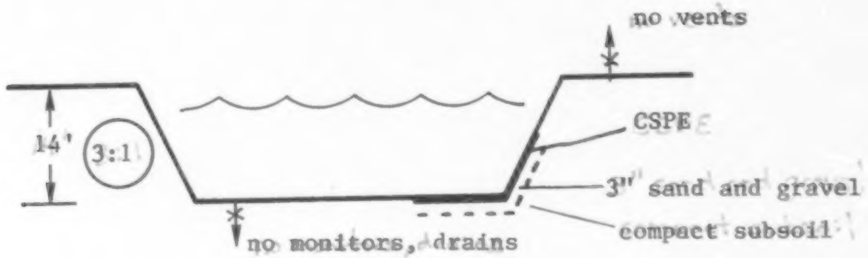
PURPOSE: Aeration basin

WASTE: Paper pulp liquor

YEARS OPERATIONAL: 2 months

PROJECTED OPERATION: closed

FACILITY: Oval with cross dike; about 8 acres



COVER: None (exposed)

PERMEABILITY: ? Sandy

BASE: Sand and gravel

GROUNDWATER: 0-5'

SUBSOIL: Sand-organic/limestone/shale

LAND: Hilly near river; previously used; sat'd w. organic sludge

LINER MATERIAL: CSPE; 30 mil; reinforced 16x8 nylon scrim; single

COMPATIBILITY: 6 months of test pond with aerator

SEAMS: Bodied adhesive factory; 6,000 LF; bodied adhesive; 100% test

NUMBER OF PARTICIPANTS: 5 (1)

PROBLEMS: Operational problems not resolved fully

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	Bottom near water table	Gas generation
LINER	Test pond incompatibility w. organic constituents 1-2% seams repaired	Whales and gas pressure rupture
APPURTENANCES	?	Lack of vents
CONSTRUCTION	No problems	Lack of lagoon bottom slope
COMMENTS:	Normal installation process	Trapped gas; not repaired due to cost; closed after 2 months

SITE: V2-3
LOCATION: Western U.S.

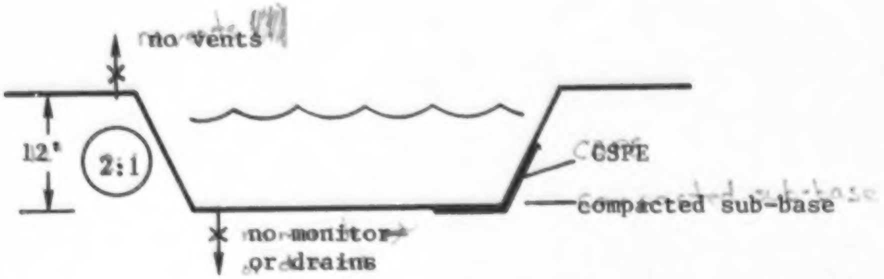
PURPOSE: Evaporation of waste

WASTE: Liquid - 15% ferrous chloride / 1.5% HCl

YEARS OPERATIONAL: 12½ years

PROJECTED OPERATION: Operating; over 20 years

FACILITY: Lagoon A; 100,000 ft²



COVER: None
PERMEABILITY: Sand-very permeable

BASE: Compacted subsoil
GROUNDWATER: 17'

SUBSOIL: ? (Sand)
LAND: Flat, on river

LINER MATERIAL: CSPE; 30 mil; unreinforced; single

COMPATIBILITY: Against similar effluent (known chemicals), verified by Manufacturer

SEAMS: Bodied adhesive factory; 1,000 LF, bodied adhesive; 100%

NUMBER OF PARTICIPANTS: 3 (?)

PROBLEMS: External

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	No problems
LINER	No problems	Rip due to truck
APPURTENANCES	-	No problems
CONSTRUCTION	No problems	No problems
COMMENTS:	Successful installation	Preventive maintenance required (fence to keep trucks off); repaired tears by cap stripping with new CSPE strips

1

SITE: V2-4 LOCATION: Eastern U.S.

PURPOSE: Sludge landfill

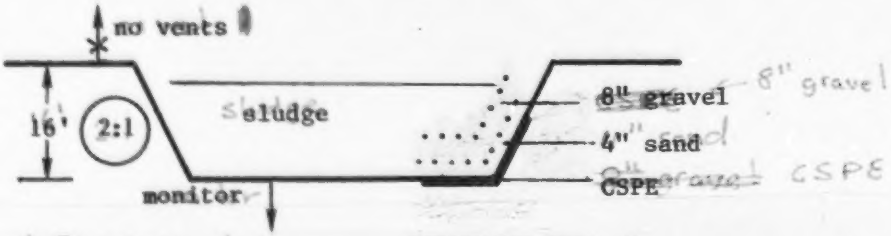
WASTE: Chemical process sludge (unknown composition)

9

YEARS OPERATIONAL: 9 years

PROJECTED OPERATION: Closed after filling

FACILITY: Phase 1: irregular trapezoidal; 186,137 ft²



COVER: – Sand and gravel

PERMEABILITY: ?

BASE: Backfill

GROUNDWATER: ?

SUBSOIL: ?, polluted w/organic material

LAND: Gently rolling; previously polluted with organic mat'ls excavated

LINER MATERIAL: CSPE; 30 mil; reinforced 8x8 nylon scrim, single (phase 1)

COMPATIBILITY: Yes, by owner

SEAMS: Bodied solvent adhesive; 2600 LF, bodied adhesive; 100% test

NUMBER OF PARTICIPANTS: 3 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	↑
SITE	No problems	No
LINER	No leaks	problems
APPURTENANCES	No problems	↓
CONSTRUCTION	Rain	
COMMENTS:	Successful installation	Containment successful after (9) years

9

SITE: V3-1 LOCATION: Northern U.S.

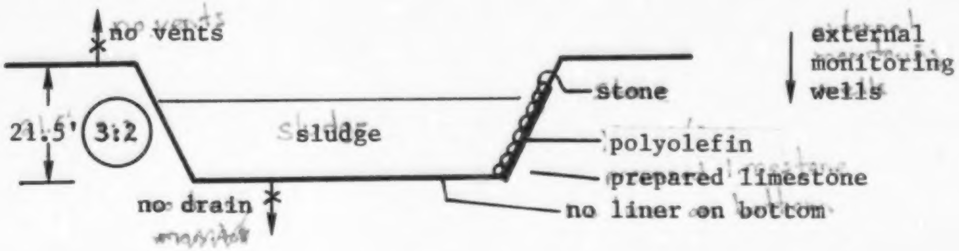
PURPOSE: Dredge material disposal

WASTE: Harbor & river dredgings; analyzed (contains oils, greases, heavy metals, cyanide, etc. Not classified as hazardous). Heavy stones.

YEARS OPERATIONAL: Less than 1 yr.

PROJECTED OPERATION: Operating up to 10 years

FACILITY: Triangular; 42 acres


no vents
external monitoring wells
stone
21.5'
3:2
sludge
polyolefin
prepared limestone
no drain
no liner on bottom

COVER: Stone (1-50 lbs.) PERMEABILITY: ?

BASE: Prepared limestone and loose aggregate bottom GROUNDWATER: ?

SUBSOIL: Silty sand/sandy clay LAND: Adjacent to lake shoreline

LINER MATERIAL: polyolefin; 30 mil; reinforced w. polyester yarn; single

COMPATIBILITY: None

SEAMS: Heat weld factory; 1300 LF, thermal weld, 100% test

NUMBER OF PARTICIPANTS: 6 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	Miscommunication
SITE	No problems	-
LINER	Tears from stones	Some external handling problem; tearing
APPURTENANCES	No problems	-
CONSTRUCTION	Underwater placement of liners - took 2 yrs.	Unusual
COMMENTS:	No problems	Operational problems worked out; successful operation after less than 1 year.

SITE: V3-2 LOCATION: Northern U.S.

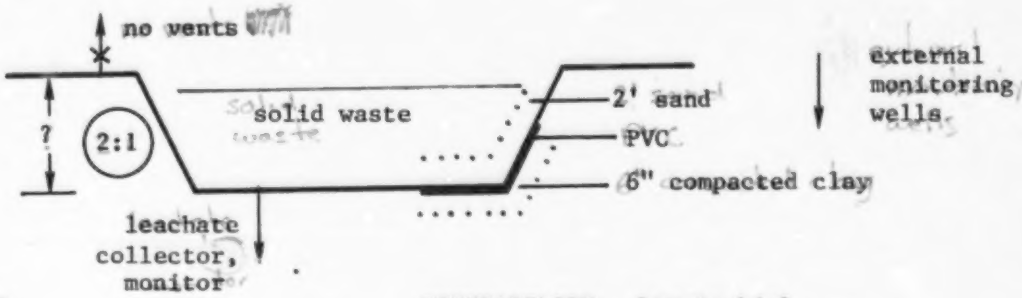
PURPOSE: Sanitary landfill, Type II

WASTE: Municipal solid waste, some petrochemical based, leachate details unknown

YEARS OPERATIONAL: 6 1/2 years

PROJECTED OPERATION: Operating, closure starting; 10 years

FACILITY: Two cells, 75 acres



COVER: Sand

PERMEABILITY: Low to high (0.0017'/day to 21.8'/day)

BASE: Clay 95% density

GROUNDWATER: At liner

SUBSOIL: Isabella loam

LAND: High; natural drainage away from site

LINER MATERIAL: PVC; 20 mil; unreinforced; single

COMPATIBILITY: None, no pretest

SEAMS: Solvent factory; ? LF; adhesive; 100% visual

NUMBER OF PARTICIPANTS: 4 (1)

PROBLEMS: Operational problems still exist

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	Inexperienced to save money
SITE	High groundwater dewatering lines to lower to 8' under liner	?
LINER	No problems	Poorly anchored?
APPURTENANCES	No problems	Poor bonding at manholes and seams suspected
CONSTRUCTION	Inexperienced crew	Leachate collector may be blocked

COMMENTS: Installation considered successful Failing - leakage detected

SITE: V3-3 LOCATION: Midwestern U.S.

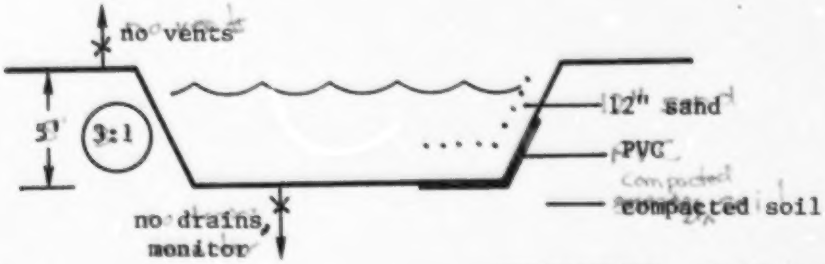
PURPOSE: Domestic wastewater stabilization pond (primary pond)

WASTE: Domestic sewage; no industrial

YEARS OPERATIONAL: 1 year

PROJECTED OPERATION: 20 years; operating

FACILITY: Primary pond; irregular rectangular; 8 acres



COVER: Sand

PERMEABILITY: Sandy soil

BASE: Graded subsoil

GROUNDWATER: ?

SUBSOIL: Sandy soil (brown silty fine sand to silty clay)

LAND: ? near wooded area

LINER MATERIAL: PVC; 20 mil; unreinforced; single

COMPATIBILITY: ?

SEAMS: ?, 100% visual

NUMBER OF PARTICIPANTS: 4 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	Wrinkles in liner	
APPURTENANCES	No problems	
CONSTRUCTION	Longer than schedule	

COMMENTS: Successful installation

Successful after 1 year (state spec 1000/gal/ac/day max allow leakage)

SITE: V3-4

LOCATION: Northern U.S.

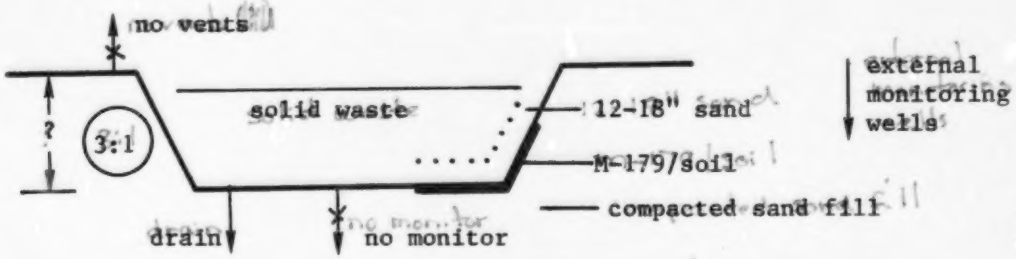
PURPOSE: Refuse landfill

WASTE: Municipal and industrial solid waste

YEARS OPERATIONAL: 8 years (?)

PROJECTED OPERATION: Functioning in part

FACILITY: Irregular; about 25 acres


no vents
?
3:1
solid waste
12-18" sand
M-179/soil
compacted sand fill
external monitoring wells
drain
no monitor

COVER: Sand

PERMEABILITY: 10^{-6} cm/sec

BASE: ?

GROUNDWATER: 2'

SUBSOIL: Coarse to fine sand/clay

LAND: Flat terrain; near housing, highway & population center

LINER MATERIAL: Dowell M-179 soil sealant, 25 T/acre, 4" thick blended with sand; single (Note: this is not a homogeneous lined site; M-179 abuts a bentonite lined portion)

COMPATIBILITY: Yes

butting

SEAMS: M-179 butting bentonite liner

NUMBER OF PARTICIPANTS: 3 (1?)

PROBLEMS: Seepage

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	?	?
LINER	Dry sand needed for blending	Subject to metal ion affects; seepage problems & mechanical rupture
APPURTENANCES	No problems	?
CONSTRUCTION	On schedule	?

COMMENTS:	Successful installation	Contamination in wells noted; Not successful due to seepage

SITE: V3-5 LOCATION: Northern U.S.

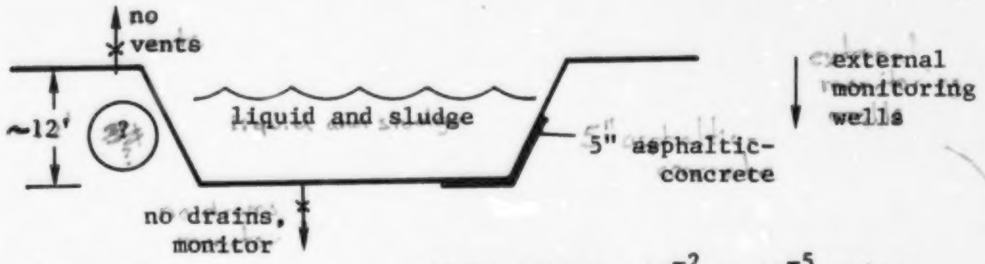
PURPOSE: Overflow storage of liquid sludge

WASTE: Liquid & sludge (non-toxic); 40% solids from paper pulp mill

YEARS OPERATIONAL: 1 year

PROJECTED OPERATION: Indefinite; operational

FACILITY: Rectangular; 30 million gals.



COVER: None (exposed)

PERMEABILITY: 10^{-2} to 10^{-5} cm/sec

BASE:

GROUNDWATER: 20'-25'

SUBSOIL: Sands and silty sands

LAND: Hilly; near river and flood plain

LINER MATERIAL: Asphaltic-concrete; 2 layers overlapped to make 5"

COMPATIBILITY: 10^{-7} perm requirement

SEAMS: ?, visual inspect

NUMBER OF PARTICIPANTS: 2 (2)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	No problems
LINER	No problems	Freeze cracking (?) easily repaired if occurs
APPURTENANCES	No problems	No problems
CONSTRUCTION	No problems	No problems

King

COMMENTS: Successful installation — Successful after 1 year

SITE: V4-1 LOCATION: Saskatchewan, Canada

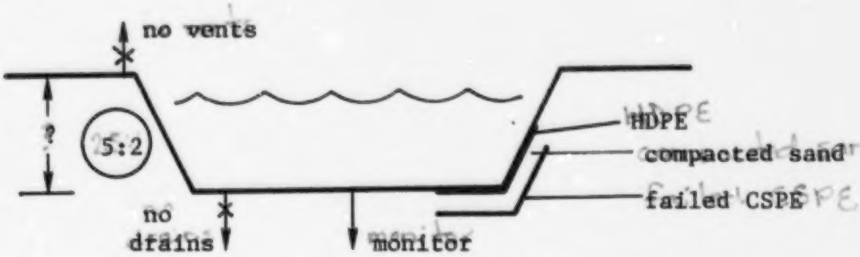
PURPOSE: Holding pond and monitoring pond

WASTE: Liquid containing heavy metals and organics

YEARS OPERATIONAL: 6 months

PROJECTED OPERATION: 20 years

FACILITY: Two rectangular cells, 18 acres



COVER: None (exposed) PERMEABILITY: ?

BASE: Sand GROUNDWATER: ?

SUBSOIL: Glacial till LAND: Rolling hills, glacial till

LINER MATERIAL: HDPE; 100 mil; unreinforced; single (NOTE: HDPE placed over existing CSPE liner)

COMPATIBILITY: None

SEAMS: 7600 M field; lap weld; 100% untrasonic test

NUMBER OF PARTICIPANTS: 5 (1)

PROBLEMS: Replaced previous 36 mil CSPE liner which failed.

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	Penetration repaired (?)	
APPURTENANCES	No problems	
CONSTRUCTION	No problems	
COMMENTS:	Successful installation	Successful after 6 months

SITE: V4-2 LOCATION: Southern U.S.

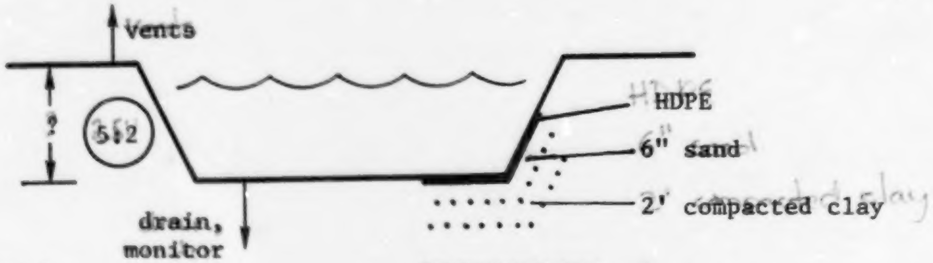
PURPOSE: Holding pond

WASTE: Brine from petroleum operation and some organics

YEARS OPERATIONAL: 4 months

PROJECTED OPERATION: 20+ years

FACILITY: Rectangular; 804,000 ft^2



COVER: Exposed PERMEABILITY: ?

BASE: Clay liner GROUNDWATER: 0 (?)

SUBSOIL: Previously polluted LAND: Flat

100 LINER MATERIAL: HDPE; 100 mil; not reinforced; double (HDPE, clay)

COMPATIBILITY: None

SEAMS: 14,300 LF field, extrusion weld, 100% ultrasonic test

NUMBER OF PARTICIPANTS: 4 (?)

PROBLEMS: Preoperations troubled

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	Poor performance; disputes	↑
SITE	Wet weather and high wind, flooding	
LINER	1% seams repaired	?
APPURTENANCES	?	
CONSTRUCTION	Walk-out; not on schedule	↓

COMMENTS: Problem plagued — Successful (?) after 4 months

SITE: V4-3 LOCATION: Southwestern U.S.

PURPOSE: Evaporation pond; power station

WASTE: Process water (less than 205°F at discharge; 110°F max for liner)

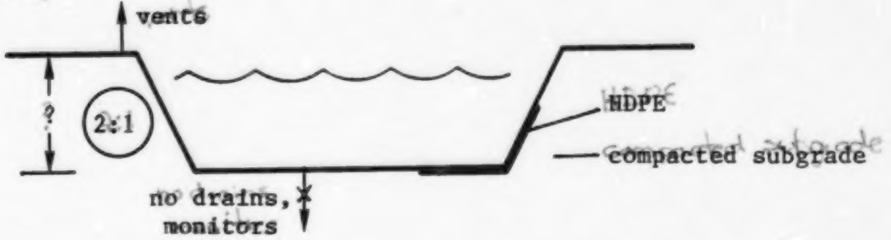
less than 1

YEARS OPERATIONAL: less than 1 year

PROJECTED OPERATION: 20+ years

FACILITY: irregular; 3,826,000 ft^2

irregular,



COVER: Exposed

PERMEABILITY: ?

BASE: Compacted subgrade

GROUNDWATER: None

SUBSOIL: Silty or clay sand

LAND: Hilly

LINER MATERIAL: HDPE; 80 mil; not reinforced; single

COMPATIBILITY: None (?)

SEAMS: 71,000 LF field, extrusion weld; 100% ultrasonic test

NUMBER OF PARTICIPANTS: 5 (?)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	No problems	
APPURTENANCES	No problems	
CONSTRUCTION	None; on schedule over 2 years	

less than

COMMENTS: Successful installation

Successful after less than 1 year

Arthur D. Little, Inc.

SITE: V4-4 LOCATION: Northern U.S.

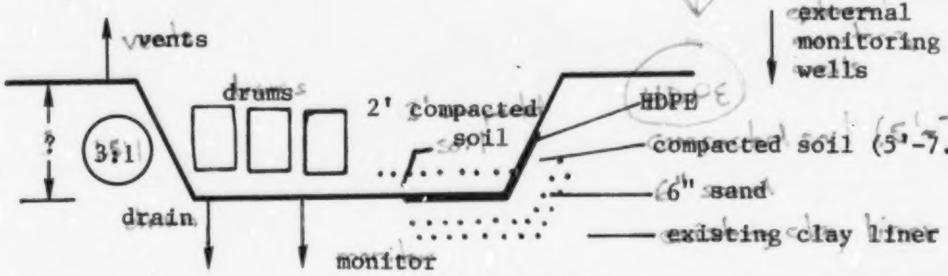
PURPOSE: Hazardous waste landfill

WASTE: In drums; wide variety; no info.

YEARS OPERATIONAL: 1 year

PROJECTED OPERATION: 6 additional months

FACILITY: Square, 262,500 ft^2


vents
drums
?
3:1
2' compacted soil
HDPE
compacted soil (5'-7.5')
6" sand
existing clay liner
external monitoring wells
drain
monitor

COVER: Slopes exposed PERMEABILITY: ?

BASE: Compact soil and sand GROUNDWATER: 10-28'

SUBSOIL: Silty clay on glacial till LAND: Hilly

LINER MATERIAL: HDPE; 80 mil; not reinforced; double

COMPATIBILITY: None

SEAMS: 9300' total; field extrusion weld; 100% ultrasonic test

NUMBER OF PARTICIPANTS: 4 (3?)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	Water	
LINER	8% seams repaired	
APPURTENANCES	No problems	
CONSTRUCTION	Moisture & low temp problems. Construction delayed 7 months	

COMMENTS: Successful installation Successful operation after one year

SITE: V4-5 LOCATION: Eastern U.S.

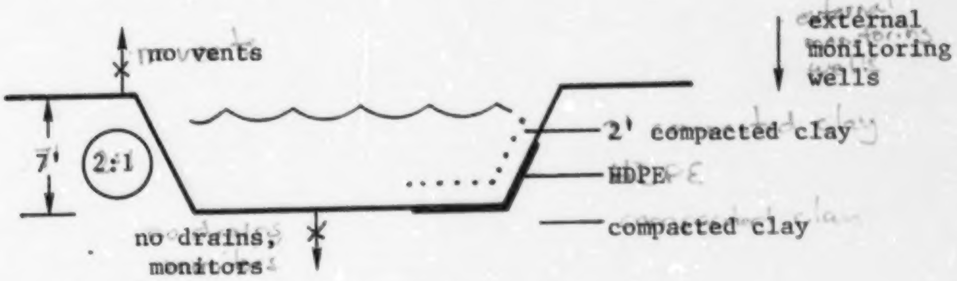
PURPOSE: Leachate collection and neutralization

WASTE: Leachate and liquid slurry from landfill

YEARS OPERATIONAL: 3 years operating

PROJECTED OPERATION: 10+ years

FACILITY: Rectangular; 141,500 ft^2


no vents
external monitoring wells
7'
2:1
2' compacted clay
HDPE
compacted clay
no drains, monitors

COVER: Compacted clay PERMEABILITY: ?

BASE: Compacted clay GROUNDWATER: ?

SUBSOIL: ? LAND: Hilly, existing landfill

LINER MATERIAL: HDPE; 80 mil; unreinforced; double

double

COMPATIBILITY: None

SEAMS: 3200 LF field; extrusion weld; 100% ultrasonic test

NUMBER OF PARTICIPANTS: 3 (2?)

PROBLEMS: HDPE over old clay site which cracked due to settling

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	3% seams repaired; penetrations repaired	
APPURTENANCES	No problems	
CONSTRUCTION	Rains delayed construction	

COMMENTS: Successful installation Successful after 3 years

SITE: V4-6 LOCATION: Eastern U.S.

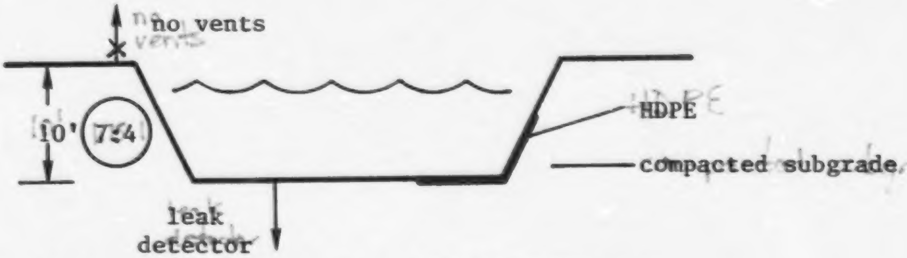
PURPOSE: Treatment pond

WASTE: Unknown comp., liquid from chem plant

YEARS OPERATIONAL: 3½ years operational

PROJECTED OPERATION: 10+ years

FACILITY: Rectangular; 11,600 ft^2; one side wall is vertical



COVER: Exposed PERMEABILITY: ?

BASE: Sand backfill GROUNDWATER: ?

SUBSOIL: ? LAND: Hilly

LINER MATERIAL: HDPE; 100 mil; not reinforced; single

COMPATIBILITY: None

SEAMS: ?; extrusion weld; 100% ultrasonic test

NUMBER OF PARTICIPANTS: 3 (0)

PROBLEMS: Hypalon in basin previously failed

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	?	
LINER	2% seams repaired; penetrations repaired	
APPURTENANCES	?	
CONSTRUCTION	Longer than schedule	

COMMENTS: Successful installation Successful after 3.5 years

SITE: V4-7 LOCATION: Western U.S.

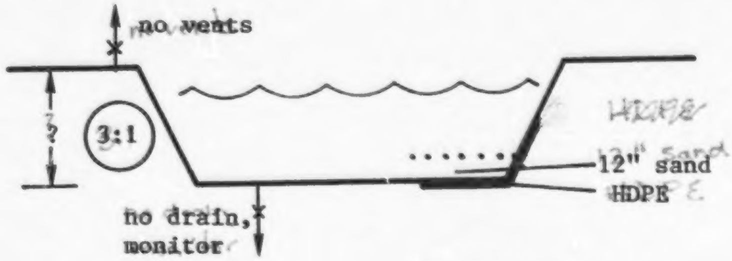
PURPOSE: Settling basin and holding ponds

WASTE: Fly ash, slurry process water, no identified organics present

YEARS OPERATIONAL: 2 years operational

PROJECTED OPERATION: 30+ years

FACILITY: 8 impoundments, 2,874,442 ft^2 total area



COVER:

PERMEABILITY: ?

BASE: Excavated subsoil

GROUNDWATER: ?

SUBSOIL: ?

LAND: Irrigated area, flat

LINER MATERIAL: HDPE; 80 mil; unreinforced; single

COMPATIBILITY: None

SEAMS: 92,600 LF field; extrusion weld; 100% ultrasonic

NUMBER OF PARTICIPANTS: 4 (2?)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	↑
SITE	Mud & water in pond	
LINER	1% seams repaired; repairs made to liner	None
APPURTENANCES	No problems	
CONSTRUCTION	No problems	↓

COMMENTS: Minimal problems; installation successful — Successful after 2 years

SITE: V5-1 LOCATION: Western U.S.

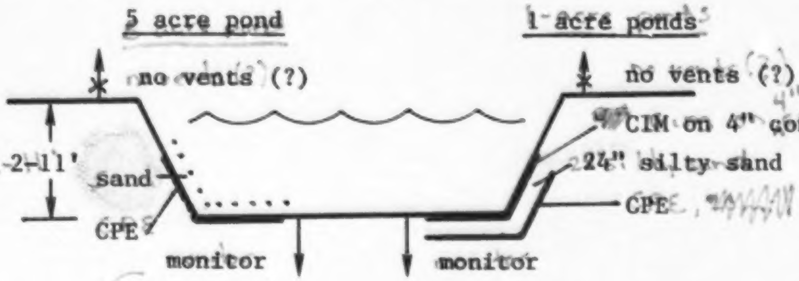
PURPOSE: Settling ponds

WASTE: Petroleum refining liquid coke slurry (122-132°F)

YEARS OPERATIONAL: 3 years

PROJECTED OPERATION: ?

FACILITY: 3 1-acre ponds, 1 5-acre pond; more than one type of construction


5 acre pond
1 acre ponds
no vents (?)
no vents (?)
2-11'
sand
CPE
CIM on 4" concrete
24" silty sand
CPE
monitor
monitor

COVER: None (?) CIM; CPE covered

PERMEABILITY: Upper soil v. permeable

BASE: Silty sand

GROUNDWATER: 150-200'

SUBSOIL: Sandy silt & clay

LAND: Near intermittent river

LINER MATERIAL: CPE/CIM CPE 20 mil/CIM /unreinforced CPE
CPE 30 mil

COMPATIBILITY: None

SEAMS: 5250'; 7270' solvent weld; visual (?)

NUMBER OF PARTICIPANTS: 6 (2)

PROBLEMS: Many in fabrication and use

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	No problems
LINER	CIM, trouble CPE, none	CIM failed; repair failed CPE functional
APPURTENANCES	?	?
CONSTRUCTION	CIM mixing difficult poor concrete cure and CIM bonding	?

COMMENTS: Failure Failure

SITE: V5-2 LOCATION: Southwestern U.S.

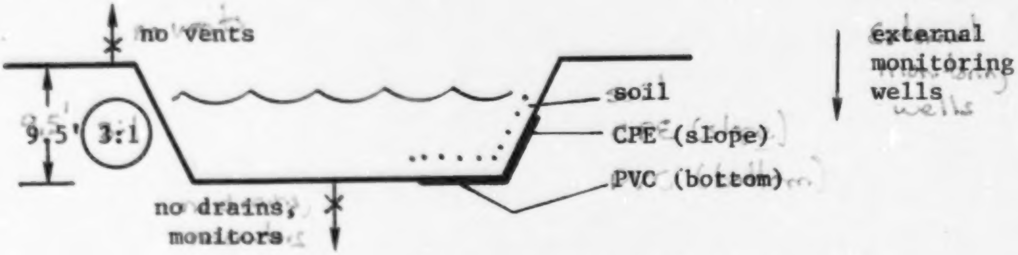
PURPOSE: Impoundment

WASTE: Uranium process water, composition unknown

YEARS OPERATIONAL: 4.5 years

PROJECTED OPERATION: On demand

FACILITY: Two cells; 100' x 5600' rectangle



COVER: Soil

PERMEABILITY: Silty sand (?)

BASE: Natural soil

GROUNDWATER: ? not encountered

SUBSOIL: Sand, gravel, loam

LAND: Sloping terrain

LINER MATERIAL: CPE - slopes; 20 mil; unreinforced; single
PVC - bottom; 10 mil; unreinforced

COMPATIBILITY: Pretest (?) unknown

SEAMS: 117,000 LF field, solvent; visual and feeler gage

NUMBER OF PARTICIPANTS: 6 (?)

PROBLEMS: Unclear

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	Poor cooperation	No problems?
SITE	?	
LINER	0.5% seam repaired; bottom damaged	
APPURTENANCES	?	
CONSTRUCTION	Longer than schedule high winds & cold	

0.5%

COMMENTS: Troubled construction, damaged liner repaired

Functional (?) after 4.5 years

SITE: V5-3 LOCATION: Western U.S.

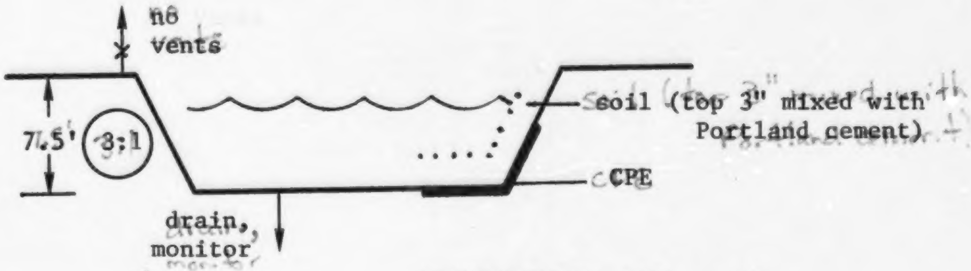
PURPOSE: Impoundment

WASTE: Refinery liquid, unknown composition

YEARS OPERATIONAL: 5 years

PROJECTED OPERATION: Closed

FACILITY: Rectangle; 240'x124'; 5/8 acre



COVER:

PERMEABILITY: Silty sand

BASE: 30 mil PVC liner

GROUNDWATER: 15-150'

SUBSOIL: Natural soil

LAND: Flat

LINER MATERIAL: CPE; 30 mil; unreinforced; single

COMPATIBILITY: None

SEAMS: 3800' field; solvent seal; feeler gage

NUMBER OF PARTICIPANTS: 5 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	
LINER	0.5% seam repair	
APPURTENANCES	No problems	
CONSTRUCTION	No problems	

COMMENTS: Successful installation

Functional, but closed after 5 years

SITE: V5-4

LOCATION: Western U.S.

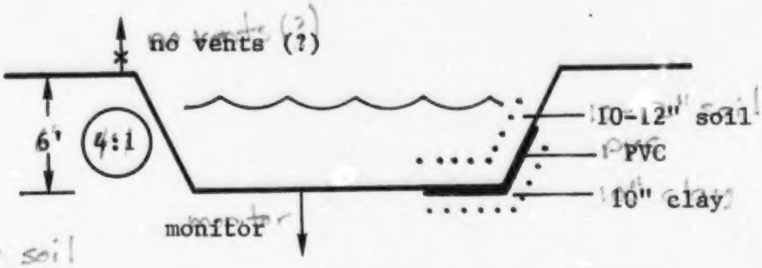
PURPOSE: Impoundment

WASTE: Cooling water for natural gas compressor

YEARS OPERATIONAL: 9 years operational

PROJECTED OPERATION: Indefinite

FACILITY: Square ponds; 1.35 acres



soil

COVER: Soil

PERMEABILITY: Silty sand

BASE: clay

GROUNDWATER: Adjacent farm wells 500'

SUBSOIL: Native soil

LAND: Slopes

LINER MATERIAL: PVC; 20 mil; unreinforced; double; sprayed asphalt on slope (?)

double;

COMPATIBILITY: ?

SEAMS: ?; solvent; feeler gage

NUMBER OF PARTICIPANTS: 4 (1)

PROBLEMS: Leak in liner repaired

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	No problems
SITE	No problems	No problems
LINER	0.5% seams repair tractor perforations	Leak repaired
APPURTENANCES	No problems	No problems
CONSTRUCTION	No problems	No problems
COMMENTS:	Successful installation	Failure (mechanical)

SITE: V5-5 LOCATION: Western U.S.

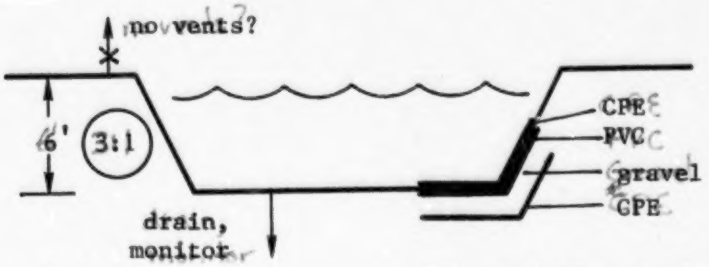
PURPOSE: Impoundment

WASTE: Process water containing chlorinated hydrocarbons (?)

YEARS OPERATIONAL: 9 years operational

PROJECTED OPERATION: Indefinite

FACILITY: Triangular; 0.75 acre



COVER: None (?) PERMEABILITY: Sandy clay

BASE: Sand GROUNDWATER: Not encountered

SUBSOIL: Excavated soil LAND: Flat

LINER MATERIAL: Triple liner - CPE 30 mil reinforced
- PVC 20 mil unreinforced
- CPE 30 mil reinforced 10x10 fiber

COMPATIBILITY: None (?)

SEAMS: ?; solvent sealing; feeler gage

NUMBER OF PARTICIPANTS: 3 (1)

PROBLEMS: No incipient failures

	PREOPERATIONAL	OPERATIONAL
PARTICIPANTS	No problems	↑
SITE	No problems	
LINER	0.5% seams repaired	No problems
APPURTENANCES	No problems	
CONSTRUCTION	No problems	↓

COMMENTS: Successful installation Functioning after 9 years